AD-A284 884

DTIC
SELECTE
SEP 2 6 1994
F

ECONOMICS OF CHLOROFLUOROCARBON (CFC) MACHINE REPLACEMENT

THESIS

Geoffrey D. Rudderow

AFIT/GEE/ENV/94S-22

DTIC QUALITY INSPECTED 3

Approved for public release; distribution unlimited

94-30611

94 9 23 022

ECONOMICS OF CHLOROFLUOROCARBON

(CFC) MACHINE REPLACEMENT

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements

for the Degree of Master of Science

in Engineering and Environmental Management

Geoffrey D. Rudderow, B.S.M.E., M.B.A.

September 1994

Accesion For		
NTIS CRA&I		☑
DTIC TAB		☐
Unannounced		☐
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

Table of Contents

List of Figures

List of Tables

Abstract

Continued use of chlorofluorocarbon (CFC) refrigerants may have a severe financial as well as operational impact on the users of air-conditioning and other refrigeration equipment as price increases continue and production is phased out. With production of CFC's coming to a halt on 31 December 1995, the two major refrigerants that have been used in commercial and industrial cooling applications will no longer be available. The phase out of production is a result of national and international agreement that these, as well as other CFC's, are a primary cause of the depletion of the stratospheric ozone layer. To help the user reduce this impact, an economic model based on the time value of money and utilizing replacement analysis was developed. The model is designed to require the user to supply information on his own equipment and on the projected costs of non-CFC replacement equipment. After running the model, the point in time when the existing equipment should be replaced is indicated. By way of example, the model is applied to a centrifugal chiller application. The results of this approach indicate that the increase in CFC costs is only a small factor in the cost of chiller operation. Rather than make a replacement to avoid the high price of refrigerant, the controlling factor is the overall cost of power consumption required to provide the cooling effect.

ECONOMICS OF CHLOROFLUOROCARBON (CFC) MACHINE REPLACEMENT

Chapter One - Overview

Introduction

As a result of the 1990 Clean Air Act Amendments (CAA) and the Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments, the manufacture and use of chlorofluorocarbons (CFC's) and hydrochlorofluorocarbons (HCFC's) are being phased out on a worldwide basis. The phase out of these substances has had and will continue to have an effect on many industries.

In our homes and daily work, there are many applications which utilize CFC's and HCFC's. The use of CFC-11 in the manufacture of insulation helps to improve the energy efficiency while increasing refrigerated space in home refrigerators; the small mechanical packages that cool the interior of refrigerators, automobiles, and the water in office water fountains use CFC-12. CFC-12 is also used in the manufacture and repair of electronic printed circuit boards and as a suspension fluid in guidance systems of some military aircraft. It has also been used as a propellant in aerosol cans. CFC-113 is used as a cleaning agent for mechanical and electrical parts in the electronic and aerospace industries. HCFC-22 is used in home and some building air conditioners.

These chemicals were originally developed in the 1930's for home refrigerators. Some CFC's and HCFC's found wide use due to their low flammability, low toxicity levels, favorable thermodynamic properties, and high stability. Due to these favorable

properties, these same materials expanded into other portions of the refrigeration market as well as into other applications including the commercial and industrial air conditioning market.

Impact On The Commercial And Industrial Sectors

While it is not the primary user of CFC's and HCFC's before the phase out, the most severe impact may be felt in the refrigeration and air conditioning industry for large applications due to the total phase out of CFC's at the end of 1995. These are applications which utilize air conditioning chillers. In April 1993, the EPA projected that with the exception of small volumes used in special applications, applications of CFC's as foaming agents, sterilants, solvents and markets other than air conditioning and refrigeration would be able to meet the January 1, 1996 phase out date (Gushee, 1993:3). It has been estimated that there were 80,000 air conditioning chillers containing CFC's as the refrigerant in 1993. Some of these chillers are being converted or replaced with chillers utilizing alternate (non-CFC) refrigerants. However, the EPA estimates that by 1996 there will still be 67,000 chillers in place that utilize CFC's. Based on the EPA's estimated leakage rate of no more than ten percent per year, these existing chillers would require five million pounds of make up refrigerant per year (Gushee, 1993:2). With production of CFC refrigerants coming to a halt as of January 1, 1996, users will need to depend on stockpiled supplies or refrigerants recycled from retired chillers.

Air conditioning chillers are high cost pieces of equipment. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) specifies that they be designed to operate for 25 years (Tuchnowski, 1994). However, many chillers have the capability to operate well beyond that. Prior to the phase out, nearly 100 percent of the chillers installed used CFC-11 or CFC-12. With the phase out, those who own these

chillers are faced with the choice of replacing the current chiller with a chiller that does not use CFC's, modifying the chiller designed to use CFC's to use an alternate refrigerant, or continuing to operate the present chiller hoping that supplies of CFC's can be found should leakage occur.

This research is concerned with the owners of older centrifugal chillers. Many organizations own centrifugal chillers which have been in operation for a number of years. The cost of operating these chillers is increasing as the cost of CFC's increases due to federal excise taxes as well as the potential effects of market forces as production decreases. The objective of this research is to develop an economic decision analysis model to determine when the replacement of this equipment should take place.

Because the model's basis will be financial, it will deal in terms of making a financial replacement decision. The costs of replacing chillers that are of various ages will be investigated in comparison with the cost of maintaining the current equipment in use.

Chapter 2, Background, will discuss how refrigerators and refrigerants operate, their impact on the environment, and the laws and treaties regarding ozone depletion. Chapter 3 will focus on the methodology used to develop the model. It presents the financial theory required to make the replacement decision, the specific information gathered for performing the analysis and shows how it will be used in development of the model. Chapter 4 will present the quantitative results of an analysis based on the application of the model. Finally, Chapter 5 will discuss implications of the results as well as make suggestions for areas of further research.

Chapter Two - CFC's As Refrigerants And The Problem They Pose To The Stratospheric Ozone Layer

Before discussing when a chiller should be replaced, it is important to know just what function CFC's and HCFC's perform in a chiller. To do this, a review of refrigeration and refrigerants is required. In addition, though federal law requires that CFC's and HCFC's be phased out, it is still important that the science, law, and treaties regarding stratospheric ozone depletion be understood.

Refrigeration

Refrigeration is a heat transfer process. The definition of refrigeration requires that heat be removed from a space that is cooler than the surrounding temperature. At home, heat is removed from the interior of the refrigerator, 40°F or lower, and rejected into the surrounding room, 70°F or greater. Home air conditioners remove heat from a building at 70°F and reject it outdoors which may be over 100°F.

Several different refrigeration systems have been developed for commercial use. These include absorption refrigeration, thermoelectric cooling, flash cooling and mechanical vapor compression refrigeration. Mechanical vapor compression is the most commonly used refrigeration system. It is used in home air conditioners, automobiles, refrigerators and air conditioning chillers.

Mechanical vapor compression refrigeration requires that a fluid be present to transfer heat from one area to another. The fluid, usually called the working fluid since it per-

forms the cooling, is the refrigerant. It moves through an airtight system, absorbing heat at one location and rejecting it at another warmer location. Starting as a low pressure, low temperature liquid at point A in Figure 2.1, the working fluid absorbs heat as it passes through a heat exchanger, the evaporator.
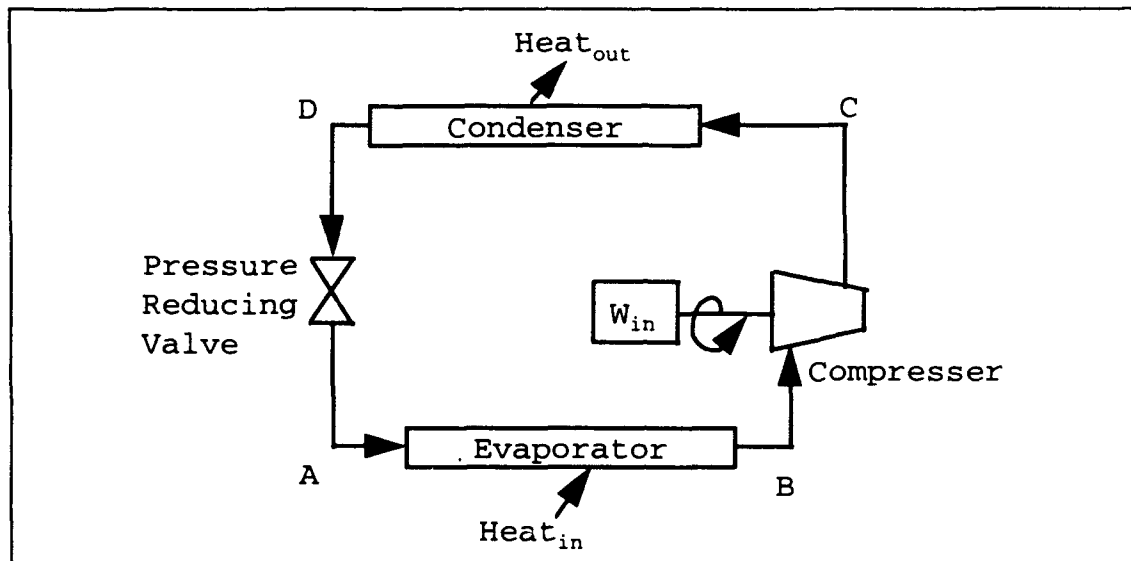
Figure 2.1 Mechanical Vapor Compression Cycle

On exiting, at point B, the working fluid has been changed to a low pressure, high temperature vaporous refrigerant. It then is passed through a mechanical compressor where work is input to the system and the pressure of the fluid is increased. The now high pressure, high temperature vapor, point C, moves through another heat exchanger, the condenser. Here heat is rejected to another fluid, usually air or water. As heat is removed, the refrigerant begins to return to a liquid state (low temperature), still at high pressure, point D. The refrigerant then passes through a pressure reducing valve to bring it to a low pressure. The refrigerant is ready to enter the evaporator again and repeat the cycle (Threlkeld 1970:41-42).

In the ideal case, with perfect heat transfer and no losses due to friction, the mechanical vapor compression system follows the Carnot cycle. Developed by Nicolas Leonard Sadi Carnot (1796-1832) the cycle is an optimum theoretical cycle. Because friction is present and heat transfer imperfect, the actual cycle used departs from the Carnot cycle by superheating the gas before it enters the compressor and subcooling the liquid as it leaves the condenser. Since the compressor is designed to handle gases, serious damage would occur if any liquid entered the compressor. By superheating, any temperature loss in the compressor will not be sufficient for condensation to occur. By subcooling, the refrigeration effect is increased and the size of the throttling valve and piping can be reduced (Wood, 1969:183-185).

When evaluating the performance of thermodynamic systems, the thermal efficiency is normally used. Thermal efficiency is the useful work output by the system divided by the heat or energy supplied to the system. In refrigeration however, the desired output is a temperature difference and work must be supplied to turn the compressor. Hence, the coefficient of performance (COP) is used. The COP is the useful refrigerating effect, $Heat_{in}$ in Figure 2.1, divided by the energy that must be supplied to the system, W_{in}. Although efficiency may never exceed unity, the COP may. Temperature difference is related to heat by the specific heat of the particular material of interest (Threlkeld, 1970:6,42).

Another common way to evaluate refrigeration equipment is to look at the amount of electrical energy that must be supplied to produce the cooling effect. For refrigeration equipment, other than electronic monitoring equipment, the major consumer of electricity is the motor used to drive the compressor. The typical measures used are kilowatts (kW) per British Thermal Unit (Btu) per hour or kW per ton.

Rating cooling in tons is a carryover from the era when ice was the principal means of refrigeration. The heat of fusion for water, the heat that must be rejected to turn water from a liquid to a solid at 32°F, is 144 Btu per pound mass (lbm). Using one ton (2,000 lbm) of water, at this rate 288,000 Btu's are rejected in a 24 hour period. This is equivalent to 12,000 Btu/hr per ton of ice. The usual practice has been that for large refrigeration units, the capacity is rated in terms of tons of capacity rather than in more conventional units (Threlkeld, 1970:42).

Refrigeration systems are available in two basic forms, those that cool directly and those that cool indirectly. In a direct system, the evaporator, condenser, or both, of the refrigeration system is in direct contact with the air to be cooled or heated. Air conditioners found in homes, automobiles, and smaller office buildings typically utilize systems of this type. These are often referred to as direct expansion (DX) units. In both the evaporator and condenser, air is either blown or drawn over finned cross-flow heat exchangers containing the refrigerant. Air that has been cooled is blown into the room or other space requiring cooling while the air that has been heated is released to the environment outside that being cooled. For a home refrigerator, the space to be cooled is the inside of the refrigerator while the exterior environment is the kitchen.

Conversely, the other type of air conditioner, a chiller, uses another medium, typically water, to cool the affected spaces. In this case, heat is first removed from the water by passing it through a shell and tube heat exchanger. The water that has been cooled, located in the chilled water supply loop, is piped to finned cross-flow heat exchangers inside air handling units (AHU's) located close to the heat load. Again air is moved through the heat exchanger and into the space requiring cooling. The water on exiting the

7

heat exchanger returns to the chiller through the chilled water return loop to be again cooled before returning the AHU.

Heat is removed from the chiller by water in the condenser water loop. Here, water is passed through the condenser shell and tube heat exchanger and piped to a cooling tower. In the cooling tower, the hot water is exposed to the air where heat is rejected to the atmosphere through both evaporation and convection. The remaining water, along with any required makeup water returns to the chiller in the condenser loop. Systems of this design can have capacities of up to 8,500 tons or 1.02×10^8 Btu/hr (York Form 160.46-PM6(193) 1993:6). By comparison, DX air conditioners in commercial applications have a maximum capacity of 50 tons.

Refrigerants

Many refrigerants have been developed since the first mechanical vapor compression system using ethyl ether as a refrigerant was patented in 1834 by Jacob Perkins. By the 1850's, refrigeration started to become commercially successful. Development continued to progress and in the 1860's, additional compounds began to be tested as refrigerants. These compounds included ammonia, carbon dioxide, sulfur dioxide, methyl chloride, and ethyl chloride (Nagengast, 1988:37).

Household refrigerators began to appear with the development of refrigeration controls, alternating current distribution systems and the induction motor. The number of household refrigerators rose at a rapid rate during the late 1920's. Technologies developed in household refrigeration led to the development of refrigeration for light commercial applications and to air conditioning (Nagengast, 1988:38)

One problem with the units then in use was that the refrigerants used were characterized by toxicity, flammability or offensive odors. While few deaths occurred, they were not without public attention. In the late 1920's, Frigidaire Corporation, fearing bad publicity, local laws restricting the use of refrigerants, and increased competition requested that General Motors (its parent company) develop a new refrigerant. The first of the chlorofluorocarbon (CFC) family of refrigerants was developed by a team led by Thomas Midbley Jr. just two days after their work began. The first CFC developed was dichloromonofluoromethane. Soon after the team developed additional refrigerants. The products were collectively given the trade name Freon®. A joint venture between General Motors and E.I. duPont deNemours and Co., Inc. began commercial production of trichlorofluoromethane and dichlorodifluoromethane in 1931 (Nagengast, 1988:38-39). They, as well as others, went on to develop additional chlorofluorocarbons (CFC's) as well as hydrochlorofluorocarbons (HCFC's) (Threlkeld, 1970:81). For the man-made refrigerants commercially in use today, they have shown, depending on the intended application (food refrigeration, food freezing, home air conditioning, etc.) both desirable thermodynamic and heat transfer properties as well as being odorless and having low flammability and acceptable toxicity (ASHRAE, 1992a:1-9).

Instead of referring to a refrigerant by chemical name, a numbering system was devised to designate the new man-made refrigerants. This system has been recognized by the refrigeration industry. It is published as a standard by ASHRAE, and has been adopted by the American National Standards Institute (ANSI) (ASHRAE, 1992a:1-9). Under the system, refrigerants based on hydrocarbons (methane, ethane, propane, and cyclobutane) and halocarbons, are numbered so that it is possible to determine the molecular structure of the refrigerant. Halocarbons are hydrocarbons where a member of the halon family (chlorine, fluorine, and bromine) has replaced one or more of the hydrogen atoms. For

example, dichlorodifluoromethane is based on the methane series. The structure of the molecule is shown below.

```
        Cl
        |
  F  -  C  -  F
        |
        Cl
```
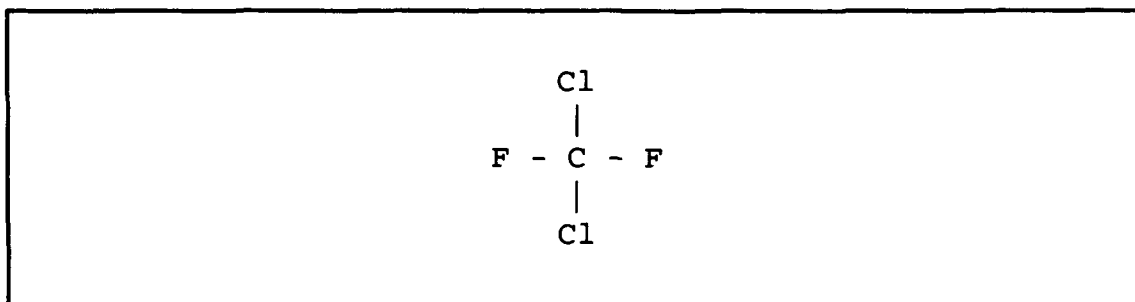
Figure 2.2 Dichlorodifluoromethane

The first digit in the numbering system is the number of unsaturated carbon-carbon bonds. For the molecule above, there is only one carbon atom so no carbon-carbon bonds exist, therefore the number is 0. The second digit is the total number of carbon atoms minus one. Again, the number is 0. The next digit is the number of hydrogen atoms plus 1. With no hydrogen atoms, the entry for dichlorodifluoromethane is 1. The last digit is the number of fluorine atoms in the molecule. Looking above, two fluorine atoms are present so the entry is 2. The refrigerant number for the molecule is then 0012. All preceding zeros are dropped, so dichlorodifluoromethane is known as Refrigerant 12 or simply R-12. It is also known by the Dupont trade name Freon® 12. This is the ozone depleting refrigerant that was used in most automobile air conditioners built prior to 1994 and is still used in home refrigerators (ASHRAE, 1992a:2-3; Schmidtt, 1994).

Should the molecule contain bromine, the same numbering system is used with the uppercase letter B after the name of the parent compound. This is followed by a number

designating the number of bromine atoms present. Thus, bromochlorofluoromethane, $CBrClF_2$ is numbered R-12B1 (ASHRAE, 1992a:3). See Figure 2.3 below.

```
                    Br
                    |
            F   -   C   -   F
                    |
                    Cl
```
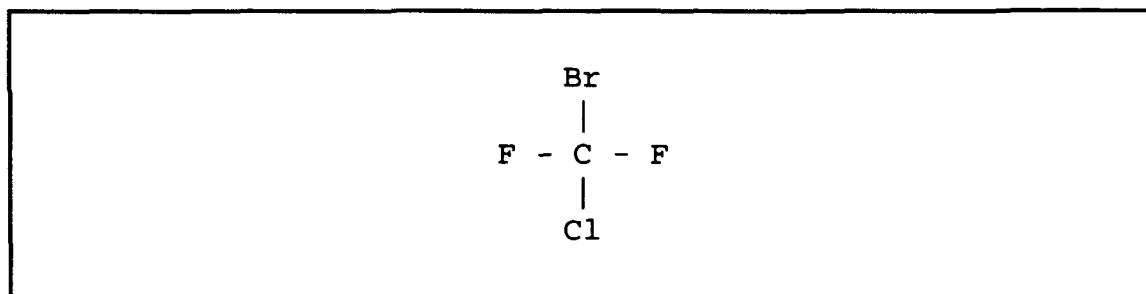
Figure 2.3 Bromochlorofluoromethane

All constituents of the molecule have been listed in the numbering system with exception of chlorine. To find the number of chlorine atoms present, subtract the number of fluorine, bromine, and hydrogen atoms from the total number of atoms that can be connected with a carbon bond. For saturated refrigerants, where no double carbon - carbon bonds exist, the number of carbon bonds is 2n + 2 where n is the number of carbon atoms. For R-12, n = 1 so the number of bonds is 2(1) + 2 = 4. There are two fluorine atoms so the number of chlorine atoms is, 4 - 2 = 2. For R-12B1, there is just a single chlorine atom since there are two fluorine and one bromine atom (ASHRAE, 1992a:2-3).

Using this system, as molecules grow larger, it is possible for two molecules to have the same number but to be chemically different. This is the case with tetrachlorodifluoroethane. See Figure 2.4.

11

```
            Cl    Cl
            |     |
      F  -  C  =  C  -  F
            |     |
            Cl    Cl

   1,1,2,2-tetrachlorodifluoroethane
               R-112


            CL    F
            |     |
      Cl -  C  =  C  -  F
            |     |
            Cl    Cl

   1,1,1,2-tetrachlorodifluoroethane
               R-112a
```
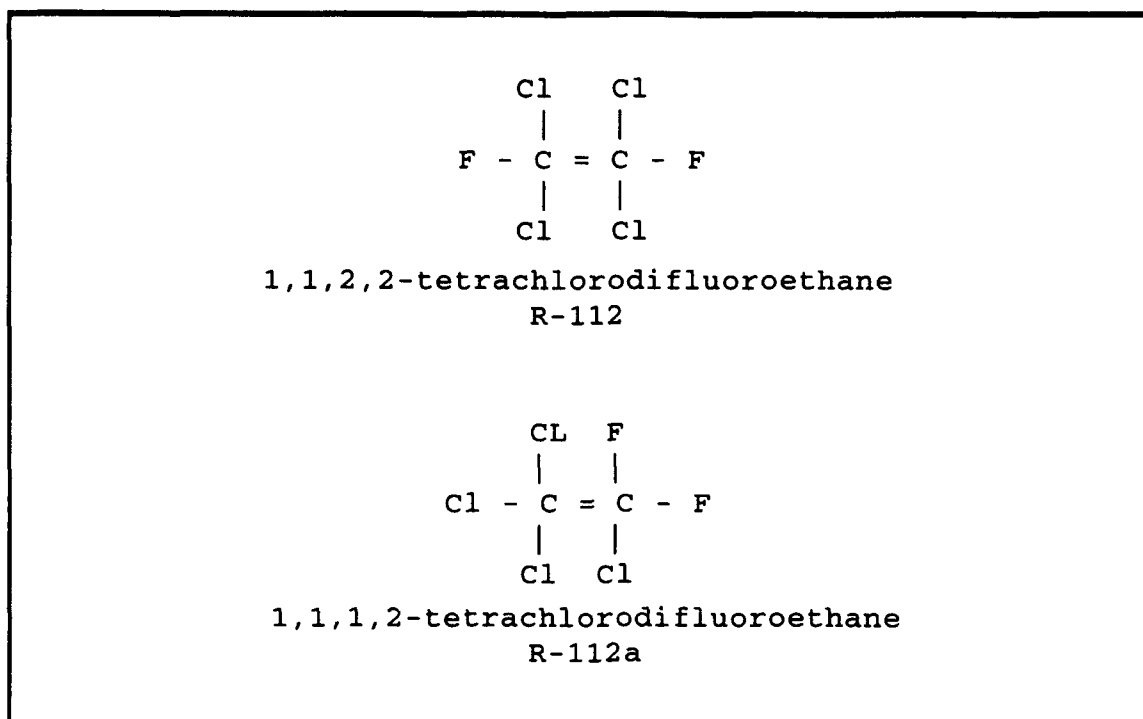
Figure 2.4 Tetrachlorodifluoroethane

In this case, each molecule contains the same atoms but they are arranged differently

about the carbon atoms. The system numbers these isomers, chemicals that have the

same formula but in different arrangement, based on the most symmetrical arrangement

of the molecule. The most symmetrical compound is designated with the applicable

refrigerant number alone. As the isomer becomes less symmetrical, successive lowercase

letters (i.e., a, b, c) are added to the refrigerant number (ASHRAE, 1992a:3).

For other refrigerants the numbering system is not quite so complex; however, it does not

convey the same information about the structure of the molecule. Zeotropes and

azeotropes, which are mixtures of two refrigerants, are numbered serially starting with

400 and 500 respectively. Refrigerants starting with 600 are miscellaneous organic

compounds that are also numbered serially. Inorganic compounds are numbered 700 plus

their molecular weights. An example is ammonia, NH_3. The molecular weight is

$14 + (3)1 = 17$, so it is R-717. For the complete standard on numbering refrigerants see

Appendix A (ASHRAE, 1992a:3).

Refrigerants that are part of the methane, ethane, propane and cyclobutane series may also

be identified with composition-designation prefixes. Rather than use the R prefix, the

number is preceded by a B, C, F or some combination thereof to designate the presence of

bromine, chlorine, or fluorine and ends in a C for carbon. Compounds that contain

hydrogen are further preceded by the letter H. Thus, dichlorodifluoromethane may also

be designated as CFC-12 and bromochlorodifluoromethane as BCFC-12B1.

Chlorodifluoromethane ($CHClF_2$) is known as R-22 or as HCFC-22 (ASHRAE,

1992a:3-4).

Before the need to eliminate the use of ozone depleting chemicals (ODC's), the

predominant refrigerants in use were CFC-11, used in chillers; CFC-12, used in chillers,

refrigerators and automobile air conditioners; and HCFC-22, used in DX air conditioners.

Since then, HCFC-123, 2,2-dichloro-1,1,1-trifluoroethane, and a hydrofluorocarbon,

HFC-134a, 1,1,1,2-tetrafluoroethane, have been identified as alternatives for CFC-11 and

CFC-12, respectively. These as well as all other refrigerants for which data has been

collected (many refrigerants have been identified but insufficient information is available)

are classified according to ANSI/ASHRAE safety standards. The classifications are by

flammability and toxicity. See Figure 2.5.

13

	SAFETY GROUP	
Higher Flammability	A3	B3
Lower Flammability	A2	B2
No Flame Propogation	A1	B1
	Lower Toxicity	Higher Toxicity

INCREASING FLAMMABILITY →

INCREASING TOXICITY →

ASHRAE 34-1992

Figure 2.5 Refrigerant Safety Group Classification

Refrigerants used inside occupied buildings, are required to be in safety groups A1 or B1. This means that there be no flame propagation when tested in air at 14.7 pounds per square inch absolute (psia) and 70°F. To receive a Class A toxicity rating, the refrigerant must have a Threshold Limit Value-Time Weighted Average (TLV-TWA) of not less than 400 parts per million by volume. Should this threshold not be met, the refrigerant receives a Class B rating. Safety ratings for refrigerants are shown in Appendix A (ASHRAE, 1992a:4-5).

Refrigerant Selection

Before designing a refrigeration system, the differences in physical properties of the refrigerants dictate that the refrigerant to be used be identified. For example, why is CFC-12 used in household refrigerators while HCFC-22 is used in home air conditioners?

One answer is that CFC-12 requires a smaller compressor, evaporator and condenser for a given heat load than does HCFC-22. Given the small space to work with in a modern refrigerator, this is the more practical choice (Schmidtt, 1994). Differences in physical properties take many forms. See Table 2.1 for a listing of some of the properties of the most widely-used refrigerants.

In the ideal case, the heat of vaporization, the heat given up when a vapor changes to a liquid at the same temperature, of the refrigerant should be relatively high. This requires a smaller quantity of refrigerant, which allows smaller heat exchangers, compressors, and pipes to be used to draw heat away from the source. This results in a smaller and less expensive system to purchase and maintain. Additionally, both the specific heat of the refrigerant and the specific volume should be low (Salas 1992:37,38). The fluid should have a moderate vapor pressure at each of the temperature limits over which it operates, to prevent the need for high pressure or high vacuum systems. Further, toxicity, corrosiveness, dielectric strength, viscosity, thermal conductivity, stability, explosiveness, and inertness need to be considered (Salas, 1992:37,38).

Commercially available chillers are of two basic designs. High pressure chillers operate where the maximum pressure is 15 pounds per square inch (gauge) (psig) or greater.

Table 2.1 Physical and Thermodynamic Properties of Common Refrigerants

Properties		Refrigerant				
		CFC-11	CFC-12	HCFC-22	HCFC-123	HFC-134a
Chemical Formula		CCl3F	CCl2F2	CHClF2	CHCl2CF3	CH2FCF3
Molecular Weight		137.4	120.9	86.47	152.9	102
Boiling Point at 1 Atmosphere	K	296.8	243.4	232.4	301.0	247.0
Critical Temp	K	471.2	385.0	369.2	457.0	374.2
Critical Pressure	kPa	4407.6	4124.9	4973.9	3673.7	4060.3
Critical Volume	ml/mol	248	217	165	279	198
Critical Density	kg/m^3	554	558	524	549	492
Density, Liquid (a)	kg/m^3	1467	1311	1192	1458	1202
Density, Sat. Vapor at Boiling Point	kg/m^3	5.86	6.33	4.72	6.57	5.18
Specific Heat, Liquid (a)	kJ/kg*K	0.87	0.97	1.26	0.99	1.43
Specific Heat, Vapor at 1 Atmosphere	kJ/kg*K	0.594	0.607	0.658	0.721	0.813
Vapor Pressure (a)	psia		95	151	14	97
Heat of Vaporization at Boiling Point	kJ/kg	180	165	234	171	218
Thermal Cond (a)						
Liquid	Btu/hr*ft°F	0.050	0.041	0.049	0.047	0.047
Vapor	Btu/hr*ft°F	0.00484	0.00557	0.00615	0.00550	0.00730
Flammability Limits in Air	vol%	none	none	none	none	none
Toxicity	ppm(v/v)	1,000	1,000	1,000	30	1,000
Odor		slightly Ethereal	Faint Ethereal	slightly Ethereal	slightly Ethereal	slightly Ethereal
Color		Colorless	Colorless	Colorless	Colorless	Colorless

(a) at 25°C

Dupont, Alternatives to Chlorofluorocarbons. Publication AG-1 (H-16411-2) (Wilmington DE: Dupont Fluorochemicls, 1992), p 6-7.
Weast, Robert C. ed., Handbook of Chemistry and Phisics, 54th edition (Cleveland OH: CRC Press, 1973), p E-34.

16

These must comply with Section VIII of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code covering the requirements for design, fabrication, inspection, and testing during construction of unfired pressure vessels. In addition, all piping, valves, fittings and other parts that are subject to the design pressure are required to be listed as complying with the ASME Code (ASHRAE, 1992b:10). The refrigerants used in these chillers are CFC-12, HCFC-22, and HFC-134a. The other types operate at a maximum pressure of less than 15 psig and are called low pressure chillers. These use CFC-11, and HCFC-123. These do not require the ASME pressure vessel certification.

The other difference in chillers is how the motor is mounted. One type of mount is an open mount where the motor is outside the flow of the refrigerant. Because motors do not convert 100% of the energy supplied to them into rotational energy, any heat produced must be removed through ventilation of the machine room. The other mount is a closed mount. Here the motor is within the flow of the refrigerant and any heat given off is removed by the chiller itself. When evaluating two machines of different motor mount design, total cooling capacity for the open mount does not include the cooling required for the motor.

Ozone Depletion

In the late 1960's and early 1970's concern surfaced about the increase in destruction of the stratospheric ozone layer (Godish, 1991:8-9). The stratosphere is a layer of the earth's atmosphere starting at ten kilometers (km) and extending to 45 km above sea level. The ozone layer has its highest concentrations between 15 and 30 km above sea level. See Figure 2.6.

In 1974, Mario J. Molina and F. Sherwood Rowland published a paper in which they stated that the most important breakdown mechanism for the two CFC's which they studied, CFC-12 and CFC-11, was through stratospheric dissociation due to ultraviolet radiation encountered at altitudes of 20 to 40 km, with the peak at 25 to 35 km. They pointed out that this was in the region of highest ozone concentration (Molina, 1974:810-811). They showed the sequence that occurred on the breakdown of CFC's. For CFC-12, chemically, CF_2Cl_2, the sequence is:

$$CF_2Cl_2 + h\nu \rightarrow CF_2Cl + Cl \tag{2.1}$$

where $h\nu$ is the energy in a photon of light, Planks constant, times the frequency of the light. The chlorine atom is then free to interact with ozone (O_3) molecules and free oxygen (O):
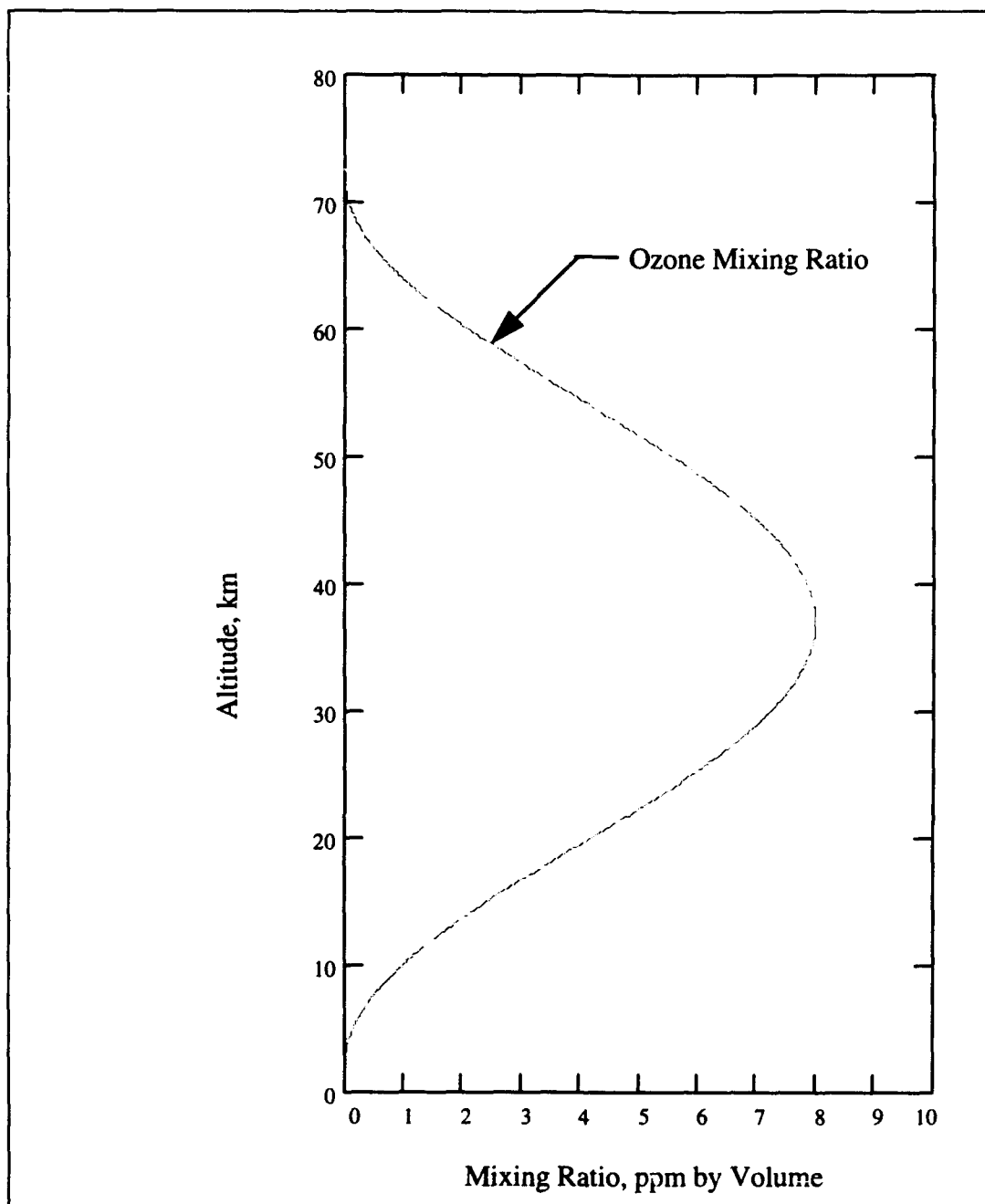
$$Cl + O_3 \rightarrow ClO + O_2 \tag{2.2}$$
$$ClO + O \rightarrow Cl + O_2 \tag{2.3}$$

Figure 2.6 Ozone Concentration in the Atmosphere

The chart shows Altitude, km (vertical axis, 0 to 80) versus Mixing Ratio, ppm by Volume (horizontal axis, 0 to 10), with the curve labeled "Ozone Mixing Ratio."

Seinfeld, John H. Atmospheric Chemistry and Physics of Air Pollution. (New York: John Wiley & Sons, Inc., 1986), p. 169.

The consequence is that an ozone molecule is destroyed and the chlorine atom has been restored, freeing it up to break down additional ozone molecules. The chlorine atom thus acts as a catalyst to break down the ozone molecules and free oxygen (O). Molina and Rowland estimated that the atmospheric lifetime of CFC-12 and CFC-11 is 40 to 150 years (Molina, 1974:810-811).

Ozone, though toxic to mammals and some plants, plays an important role concerning life on earth. Ultraviolet rays, x-rays, and gamma rays that could potentially harm life on earth are absorbed by ozone molecules and other chemicals in the atmosphere (Fredrick, 1976:253). Depletion of the ozone layer, even to a small degree, could cause a significant increase in the number of cases of skin cancers, particularly among lightly pigmented Caucasians. In addition, concerns have been raised about the effect of the increased radiation exposure to aquatic life in the Antarctic. Should photoplankton be adversely affected, it is possible that other species that feed on them, as well as other members of the food chain including fish, birds and whales could suffer. Furthermore, agriculture may be affected by stunted growth and reduced yield of some crops (Godish, 1991:116,117).

The first federal legislation came in response to a number of studies that were done after the Rowland-Molina theory was first forwarded. In House Conference Report No. 95-564, reasoning is given for the inclusion of a section on Stratospheric Ozone Depletion in Public Law 95-95, The Clean Air Act, adopted May 12, 1977 (United States House of Representatives, 1977:94).

Discussed in the report was a study done in August 1975 by the National Bureau of Standards that produced highly convincing evidence that halocarbon molecules dissociate in the presence of ultraviolet light. In addition, the study cites findings of tests performed

by the National Oceanographic and Atmospheric Administration (NOAA) in September 1975 which found hydrochloric acid (HCl), an additional sink for chlorine atoms, at altitudes as high as 28 km. The concentrations of HCl were found to increase with altitude. Concentrations of CFC-11 and CFC-12 however disappeared above 42 km and 58 km respectively. That month results from tests performed by the Jet Propulsion Laboratory (JPL) were also released. These showed that HCl levels from ground levels decreased to the point where they could not be measured at an altitude of seven km. However, HCl reappeared in greater concentrations at an altitude of 15 to 16 km. Higher concentrations of HCl were found at increased altitudes. This finding ruled out one of the alternative explanations to the Rowland-Molina theory. The alternate theory held that chlorine atoms in the upper atmosphere might be inserted due to natural causes rather than to photodissociation. If the alternate theory were correct however, HCl would be expected to occur throughout the atmosphere rather than just in the 15 to 28 km zone. Rather, this finding implies that at higher altitudes, these refrigerants that are so popular for their stability break up with some of the chlorine associating itself with hydrogen atoms (United States House of Representatives, 1977:96-97)

The House report stated that to date, it was estimated that the ozone layer had been depleted by 1 percent due to past halocarbons released. It also estimated that if no further releases of halocarbons took place, ozone layer depletion would increase to 2 percent due to the time required for diffusion into the stratosphere. Further calculations predicted that if releases continued at the 1972 rate, the depletion would increase to 7 percent by the time equilibrium was reached. In addition it was predicted that more than a century would be required to reestablish the ozone layer once releases had been stopped (United States House of Representatives, 1977:94-95).

The House report stated that because of the high variability of the ozone layer, ozone depletion by halocarbons that had been released to date had not been measured. It pointed out that ozone concentration varies daily, seasonally, and in an eleven-year cycle in phase with the solar sunspot cycle. It pointed out that to wait for a statistically measurable change would require that future generations bear the consequences of skin cancers that would then need be linked back to a reduction in the stratospheric ozone layer (United States House of Representatives, 1977:95).

The House report finally pointed out that besides CFC's, other substances threaten the ozone layer. These included emissions from aircraft flying in the stratosphere, bromide compounds, sources of chlorine other than CFC's, and nitrogen oxides (United States House of Representatives, 1977:95).

The primary purpose of the section on ozone protection in the 1977 Clean Air Act was to call on the Environmental Protection Agency (EPA), as well as other government departments and agencies, working alone or together, to perform research and monitoring activities on ozone layer depletion. It also directed the President to enter into international agreements for research and for the development of standards and regulations for the protection of the ozone layer. Finally, it directed the EPA to promulgate regulations for the control of ozone depleting substances. The regulations were to take into account the feasibility and cost of achieving control (United States House of Representatives, 1977:99-103).

Based on this law, in 1978 the EPA banned the use of CFC's as aerosol propellants in all but certain medical applications. Similar bans were put into place in Canada and Sweden in the same year, also as a result of the Rowland-Molina theory. The result was an estimated reduction in the use of CFC's by 40% in this country. However due to growth

22

in the use of CFC's in other traditional markets, the reduction in CFC's was overcome by 1983 (Godish, 1991:273).

The Vienna Convention for The Protection of The Ozone Layer (Vienna Convention) was the first international agreement to deal with ozone depleting chemicals (ODC's). Negotiated under the auspices of the United Nations Environment Programme, twenty-two countries, including the United States, signed the convention on March 22, 1985. The agreement entered into force on September 22, 1988. At this meeting, the parties to the agreement recognized that depletion of the ozone layer was a worldwide problem and that only through an international effort could the problem be better defined and a solution found. The convention called on all parties to make a joint effort at sharing information and technology to reduce the problem of ozone depletion. In addition, the convention set up a schedule for future meetings (Ozone Secretariat, 1993:129-135,143,150-156).

In 1985, the "Ozone Hole" over Antarctica was revealed. British scientists observed a significant decline in stratospheric ozone during October of each year with declines beginning in the late 1970's and increasing in severity thereafter. Calculations made in 1987 showed that the ozone levels were 50% of their 1979 levels. (Godish, 1991:112,113)

The Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) signed on September 16, 1986 and taking effect on January 1, 1989, was the first international agreement to begin to reduce the overall use of chlorinated chemicals (United States Senate, 1987:9). Amending the Vienna Convention, the signatories, which included the United States, agreed that beginning seven months after coming into force, each year each country's calculated consumption, defined as the amount produced less the

amount exported plus the amount imported, of CFC's would not exceed that country's

calculated level for 1986. This applied to CFC-11, CFC-12, CFC-113, CFC-114, and

CFC-115. Allowances were provided for developing countries where consumption was

0.3 kilograms or less on an annual per capita basis (United States Senate, 1987:2,6).

The signatories also agreed that for each year starting February 1, 1992 after the protocol

came into effect, calculated levels of Halon 1201, Halon 1301, and Halon 2402 would not

exceed 1986 consumption levels. Halon is used as a fire suppressant. The formulation

contains chemicals in the halon group. Again, allowances were provided for developing

countries (United States Senate, 1987:2,6).

In addition, the protocol required that for the period July 1, 1993 to June 30, 1994,

consumption of the CFC's listed not exceed 80% of the 1986 consumption levels. This

was further reduced to 50% for the year ending June 30, 1999 (United States Senate,

1987:2,3).

Other articles within the Montreal Protocol established a system for calculating levels of

the substances covered. In addition, within one year of the protocol going into force,

imports from countries that had not signed the protocol were prohibited. Further, the

protocol banned the export of covered substances to countries that were not signatories or

had otherwise conformed to it as of January 1, 1993. The ban went so far as to include

products made with the banned substances, technology used to produce those substances,

and aid in procuring equipment to manufacture the substances (United States Senate,

1987:5).

The protocol also called on the signatories to meet periodically beginning in 1990.

Among their charges was to determine if any changes are required in the protocol to keep

abreast of new research, to devise a method to determine non compliance, and to decide how parties who are not complying the protocol should be dealt with (United States Senate, 1987:5-7).

The London Amendments to the Montreal Protocol, signed in 1990, recognized that other CFC's, HCFC's, as well other chemicals also contributed to the ozone depletion problem. These amendments required that for the 1993 calendar year consumption of CFC-13, CFC-111, CFC-112, CFC-211, and CFC-212 through CFC-217 not exceed 80% of their annual calculated levels for 1989. For calendar year 1997, consumption is not to exceed 15% of the 1989 level. Finally, consumption levels are to go to zero by January 1, 2000 (United States Senate, 1991:3-4,13).

The London amendments also made additional changes concerning trade between countries and in setting up an appeal system for developing nations. Further, though no schedule for elimination was set up in the text of the agreement, an annex was added which listed all HCFC's known at the time under the heading "Transitional Substitutes" (United States Senate, 1991:6-7,14-15). The amendment entered into force on August 10, 1992 (Ozone Secretariat, 1993:3).

To put the international agreements into place in federal law, the President signed Public Law 101-549, the Clean Air Act Amendments of 1990. The law repealed the 1977 CAA sections dedicated to stratospheric ozone protection and added Title IV - Stratospheric Ozone Protection as a replacement (Arbuckle, 1993:138). The new CAA contained a phase out schedule that was at least as strict as the Montreal Protocol (United States Congress, 1990: Sec 604).

Section 603 of the new CAA classified and grouped CFC's, halons, carbon tetrachloride, methyl chloroform, and HCFC's. See Table 2.2. Sections 604 and 605 established phase out schedules for CFC's, HCFC's, carbon tetrachloride and methyl chloroform. See Table 2.3 for the phase out schedule of Class I substances. For Class II substances, effective January 1, 2015, it is illegal to produce a greater quantity of a Class II substance than was produced in the prior year. January 1, 2020, it is illegal to use new material (versus recycled or recovered material) unless it is used as a refrigerant in appliances manufactured before January 1, 2020. Finally, effective January 1, 2030, it is illegal to produce any class II substance. For both class I and class I substances, specific exemptions exist. However, these must be within the allowances of the Montreal Protocol. (United States Congress, 1990: Sec 603-605).

In addition, Section 606 gave the Administrator of the EPA the authority to promulgate regulations that were stricter if, based on credible scientific information, such action is required to protect human health and the environment; or based on the availability of substitutes, a more stringent schedule is practical; or if the Montreal Protocol were modified to include a schedule to reduce production, consumption, or use more rapidly than Section 604 and 605 of the title. The new CAA also called on the EPA Administrator to establish standards regarding the use and disposal of class I and class II substances during the service, repair, or disposal of household, commercial, and automobile air conditioners, refrigerators, chillers, or any other equipment that used a class I or class II substance as a refrigerant (United States Congress, 1990: Sec 606, 609,615).

Table 2.2 List of Class I and Class II ODC's

Class I

Group I

CFC-11	CFC-114
CFC-12	CFC-115
CFC-113	

Group II

Halon-1211	Halon-2402
Halon-1301	

Group III

CFC-13	CFC-213
CFC-111	CFC-214
CFC-112	CFC-215
CFC-211	CFC-216
CFC-212	CFC-217

Group IV

carbon tetrachloride

Group V

methyl chloroform

Class II

HCFC-21	HCFC-142	HCFC-235
HCFC-22	HCFC-221	HCFC-241
HCFC-31	HCFC-222	HCFC-242
HCFC-121	HCFC-223	HCFC-243
HCFC-122	HCFC-224	HCFC-244
HCFC-123	HCFC-225	HCFC-251
HCFC-124	HCFC-226	HCFC-252
HCFC-131	HCFC-231	HCFC-253
HCFC-132	HCFC-232	HCFC-261
HCFC-133	HCFC-233	HCFC-262
HCFC-141	HCFC-234	HCFC-271

United States Congress, Public Law 101-549, 104 Stat. 2650, Sec 602(a)-(b).

Table 2.3 Phase Out Schedule for Class I ODC's

Production Permitted as a Percent of the 1986 Baseline Level

Year Beginning Jan 1	CFC's Group I and III	Halon Group II	Carbon tetrachloride Group IV	Methyl chloroform Group V
1994	25	0	50	50
1995	25	0	15	30
1996	0	0	0	0

Environmental Protection Agency, "Protection of Stratospheric Ozone; Final Rule," Federal Register, 58: 65021 (10 December 1993).

At a meeting in Copenhagen on November 25, 1992, the parties to the Montreal Protocol agreed to accelerate the phase out of CFC's. Adjustments to the Protocol reduced consumption to 25% of the 1986 consumption level as of January 1, 1994. A total ban on consumption, with some variance for critical uses, is to go into effect on January 1, 1996 (Copenhagen Revisions to the Montreal Protocol, 1992).

The Copenhagen amendments to the Montreal Protocol will freeze consumption of HCFC's in 1996. The consumption cap will be at 100 percent of 1989 HCFC consumption plus 3.1 percent of the 1989 CFC consumption. By 2004, the consumption level will be reduced to 65 percent of the cap. Reductions will continue to 35 percent in 2010, 10 percent in 2015, and 0.5 percent in 2020. Consumption of HCFC's will be phased out by 2030. Other amendments required that hydrobromofluorocarbons (HBFC's), be phased out by 1996. Further, they required that bromomethane (CH_3Br) be frozen in 1995 at 1991 levels and that future reductions be based on pending scientific assessments (Copenhagen Revisions to the Montreal Protocol, 1992).

In addition, the Copenhagen Revisions adopted a procedure for the approval of production and consumption of chlorofluorocarbons in what were deemed essential uses. Essential uses were defined as necessary for health or safety, or critical to the functioning of society and no available alternatives or existing stocks of banked or recycled material available (Copenhagen Revisions to the Montreal Protocol, 1992).

On December 10, 1993, the EPA issued final regulations on the phase out of ODC's to remain at least as stringent as the international agreements. All CFC's, HCFC's as well as other ODC's are scheduled for phase out as called for in the most recent amendments of the Montreal Protocol. While at this time a specific schedule for the phase out of all HCFC's is not included (the law referred the reader back to the Montreal Protocol) there are several exceptions. The first is that production of HCFC-141b is prohibited after January 1, 2003. The second deals with HCFC-142b and HCFC-22. For both these materials, effective January 1, 2010, they may only be used in equipment manufactured before the effective date. Effective January 1, 2020, it will be illegal to produce them. The last deals with HCFC's in general. Effective January 1, 2015, HCFC's may only be used as refrigerants for equipment built before January 1, 2020. HCFC's are banned effective January 1, 2030 (Environmental Protection Agency, 1993:65064,65065).

Chapter Three - Model Development

Introduction

As discussed in the previous chapter, national and international steps are being taken to phase out CFC's and HCFC's in an effort to reduce depletion of stratospheric ozone. The result is that those who have chillers using these chemicals need to decide what steps to take and when in order to assure themselves of having cooling capacity in the future. This chapter develops an economic model designed to help make that decision. Before the model can be discussed, it is important to review the basics of the time value of money, and replacement analysis.

Time Value Of Money

In simplest terms, the time value of money reflects the fact that it is preferable to have a dollar today rather than one year from today. This is because the dollar today can be placed in a bank account and will, in one year, be worth more than one dollar due to the interest earned. Using a simple interest rate of 5%, one would expect to receive $1(1.05) or $1.05 in one year.

Simple interest is based on a fixed interest rate paid over a period. If p represents the principal, i the interest rate, and n the number of interest periods then:

$$I = (p)(n)(i) \qquad (3.1)$$

where I is the interest paid. For example, if $1,000 were invested in a one-year certificate of deposit at an interest rate of 5%, the interest paid would be:

$$I = \$1,000(1)(0.05) \qquad (3.2)$$

$$I = \$50. \qquad (3.3)$$

Another common type of interest is compound interest. Here, interest is paid at the end of some pre-specified period. The principal and interest earned continue to stay in place however and interest is earned on the interest. One thousand dollars is deposited in a bank account at an interest rate of 5% compounded annually. What will the total value of the account be after five years? The calculation can be performed using a spreadsheet as shown in Table 3.1.

Table 3.1 Compound Interest

Year	Value at Beginning of Year p	Interest to be Added at End of Year p(i)n = I	Value at End of Year p + I	Amount to be Received at the End of 5 Years
	A	B	(A + B)	
1	$1,000.00	$1,000.00 X .05 = $50.00	$1,050.00	$0
2	$1,050.00	$1,050.00 X .05 = $52.50	$1,102.50	0
3	$1,102.50	$1,102.50 X 0.05 = $55.13	$1,157.63	0
4	$1,157.63	$1,157.63 X 0.05 = $57.88	$1,215.51	0
5	$1,215.51	$1,215.51 X 0.05 = $60.78	$1,276.28	$1,276.28

Rather than go through the series of spreadsheet calculations to determine what the value of the investment will be, another method is available. For the first year, the value is $1,000 X 1.05 = $1,050. For the next year, the value is $1,000 X 1.05^2 = $1,102.50. After five years, the value will be $1,000 X 1.05^5 = $1,276.28. This defines the formula for future value or future worth:

$$F = P(1 + i)^n \qquad (3.4)$$

where P represents the present value of the funds invested and F the value of the money after n periods earning an interest rate of i. To put the equation in terms of present value it can be manipulated to:

$$P = F/(1 + i)^n \qquad (3.5)$$

To this point, compounding has occurred on an annual basis. However, compounding may occur on a more frequent basis such as monthly or quarterly. When the compounding rate is other than once per year, the actual interest rate for each compounding period must be calculated. In addition, to use present value methods, time must be expressed in terms of the number of compounding periods. Thus the interest rate (i) for a period less than one year is calculated as:

$$i = r/m \qquad (3.6)$$

where r is the nominal annual interest rate and m is the number of compounding periods per year. The total number of compounding periods n is the number of years the investment will be in place times m.

If \$1,000 is invested at 5% per year compounded quarterly for a period of five years the total return can easily be calculated. Since r, the nominal annual interest rate is 5%, and m is four periods per year, the actual interest rate is:

$$i = (5\%/\text{year})/(4 \text{ periods/year}) \qquad (3.7)$$

$$i = 1.25\% \text{ per period.} \qquad (3.8)$$

The number of periods is:

$$n = (\text{number of years})(m) \qquad (3.9)$$

$$n = (5 \text{ years})(4 \text{ periods/year}) \qquad (3.10)$$

$$n = 20 \text{ periods} \qquad (3.11)$$

So now,

$$F = P(1 + i)^n \qquad (3.12)$$

$$F = \$1,000(1 + .0125)^{20} \qquad (3.13)$$

$$F = \$1,000(1.282037) \tag{3.14}$$

$$F = \$1,282.04 \tag{3.15}$$

This compares to the $1,276.28 when compounding was done annually in the previous example.

Another calculation that can be made is one where the present value of a uniform series of payments, an annuity, is calculated. For example, if $100 is to be received at the end of years one and two, and the interest rate is 5% compounded annually, what is the present value of the series of payments? One way to determine the present value is to set up calculations for each year and then add them:

$$P = F_{yr1}(1 + i)^{-1} + F_{yr2}(1 + i)^{-2} \tag{3.16}$$

$$P = \$100(1 + .05)^{-1} + \$100(1 + .05)^{-2} \tag{3.17}$$

$$P = \$95.24 + \$90.70 \tag{3.18}$$

$$P = \$185.94 \tag{3.19}$$

An alternate calculation is:

$$P = A\{[(1 + i)^n - 1]/i(1 + i)^n\} \tag{3.20}$$

$$P = \$100\{[(1 + .05)^2 - 1]/.05(1 + .05)^2\} \tag{3.21}$$

$$P = \$100\{.102500/.055125\} \tag{3.22}$$

$$P = \$185.94 \tag{3.23}$$

where A is the amount of the annuity to be paid or received annually in each of n years. See Appendix B for a derivation of the equation. This is called the uniform series present worth factor. It is denoted by (P/A,i,n). When the annuity is being calculated from the present worth, the capital recovery factor is being calculated. This is (A/P,i,n) (Grant, 1976:35-37).

If the cost of maintaining a piece of equipment increases at a uniform rate over its life, the uniform gradient series can be used to calculate the equivalent equal annual payment. Assume that in the first year, the cost of maintaining an air conditioning system is $1,000. It is estimated that the cost of maintenance will increase by $100 each year over the five year life of the equipment. Using an interest rate of 5%, what would the equivalent equal annual payment be?

The cash flows for maintenance of the air conditioner would be:
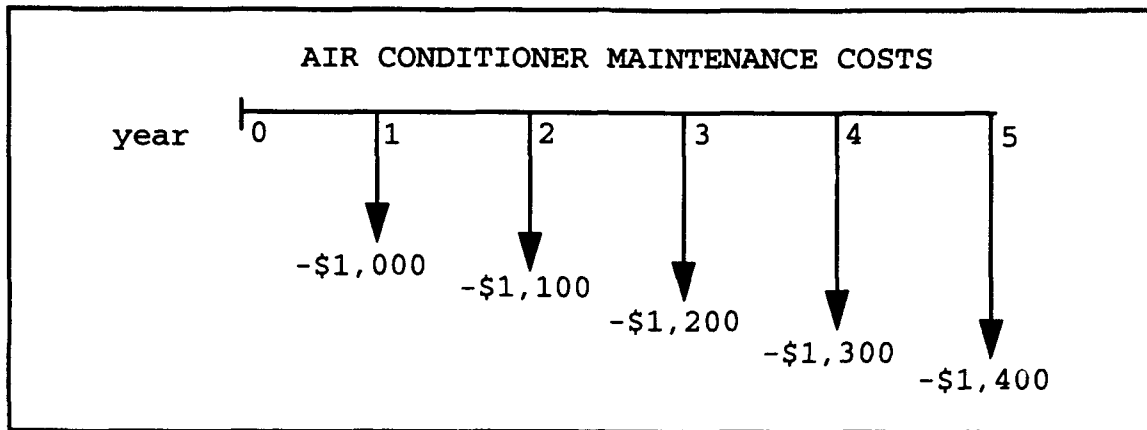
Figure 3.1 Cash Flow For Uniform Gradient Example

One way to make the calculation is to take each of the cash flows above, determine its present value P, then using the equal payment-series capital-recovery calculate A. So:

$$P = \sum_{n=1}^{5} (F_n(1 + i)^n) \tag{3.24}$$

and $A = P(i(1 + i)^n)/((1 + i)^n - 1)$ \hfill (3.25)

The Uniform Gradient-series method takes advantage of the fact that the increase is equal in each year. As a result, the following equation is used:

$$A = A_1 + A_2 \tag{3.26}$$

where A_1 is the cost at the end of year one and A_2 represents the cost of the gradient where it is equal to

$$A_2 = G((1/i) - (n/i)(i/((1 + i)^n - 1)) \tag{3.27}$$

or $\quad A = A_1 + G((1/i) - (n/i)(i/((1 + i)^n - 1)) \tag{3.28}$

where G is the gradient or the difference between the cost in the first and second years. The term $(1/i) - (n/i)(i/((1 + i)^n - 1))$ is called the gradient factor and is represented as $(A/G,i,n)$. For the example,

$$A = \$1,000 + \$100((1/0.05) - (5/0.05)(0.05/((1 + 0.05)^5 - 1)) \tag{3.29}$$

$$A = \$1,000 + \$100(1.9025) \tag{3.30}$$

$$A = \$1,190. \tag{3.31}$$

Therefore, given the time value of money, the cash flow pattern shown above is equivalent to spending \$1,190 in each of the five years.

The illustrations thus far have concentrated on looking at present values and a series of equal payments made over a time period. As one might assume, by reversing the equation it is also possible to calculate future values from present values, and future values from a series of equal payments as well as present and future values from a uniform gradient. Formulas for these as well as the formula used in continuous compounding are found in Appendix C. Rather than use the formulas just described,

many engineering economics and engineering handbooks contain tables of compounding factors for various interest rates and periods.

When calculating the present value of an investment, one looks at when cash flows occur. For instance, suppose a pump is purchased for $2,100, annual operation and maintenance cost is expected to be $100 and there is an expected salvage value of $100 in five years. The cash flows could be set up as shown below:
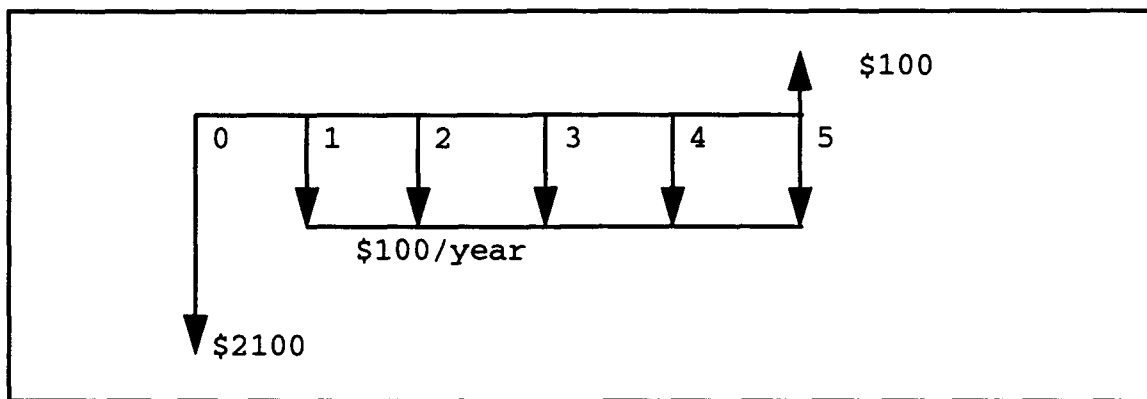
Figure 3.2 Cash Flows for Present Value Analysis

Assuming an interest rate of 7% and these cash flows, the present value for the entire project can be calculated.

$$P = -\$2,100 - \$100(P/A,7,5) + \$100(P/F,7,5) \qquad (3.32)$$

$$P = -\$2,100 - \$100(4.1002) + \$100(0.7130) \qquad (3.33)$$

$$P = -\$2,438.72 \qquad (3.34)$$

The calculation shows then that even though a total of cost of $2,500 will be realized over the life of the pump, the total cost, at the present time, is $2,438.72.

Financial Accounting And Depreciation

No distinction has yet been made between costs and expenses. "Cost is the sacrifice made, the benefits foregone, or the resources consumed in the acquisition of an asset (Spiller, 1977:37)." There are two kinds of costs, those that are involved with production of current revenue, expenses, and those that are involved with production of future revenue, assets. A cost becomes an expense when the asset is consumed in the production of revenues (Spiller, 1977:20).

The term depreciation is used to indicate that the service potential of a tangible asset has declined. In accounting, depreciation is a system of cost allocation rather than a matter of valuation. Assets are depreciated on the basis of a systematic charge to expense rather than on the basis of a decline in their fair market values. "Depreciation is defined as the accounting process of allocating the cost of tangible assets to expense in a systematic and rational manner to those periods expected to benefit from the use of the asset" (Kieso, 1992:543).

The Financial Accounting Standards Board (FASB) has defined depreciation as:

> The cost of a productive facility is one of the costs of the services it
> renders during its useful economic life. Generally accepted accounting
> principles [GAAP] require that this cost be spread over the expected useful

39

life of the facility in such a way as to allocate it as equitably as possible to the periods during which services are obtained from the use of the facility. This procedure is known as depreciation accounting, a system of accounting which aims to distribute the cost or other basic value of tangible capital assets, less salvage value (if any), over the estimated useful life of the unit...in a systematic and rational manner. It is a process of allocation, not of valuation. (Financial Accounting Standards, 1977:Chapt. 9, Sec. C, Par.5)

Thus, depreciation distributes the cost of an asset over its useful life. It makes no attempt to track the value of the asset during its life. The result is that depreciation recognizes the cost of an asset by expensing it over the periods in which it is consumed. For tangible assets however, the cost is of interest, not the expense. An alternate way to look at this is based on the use of the asset. If an asset is purchased, but never put into service, it cannot be depreciated, because no period benefits from its use. However, there has still been a cost in procurement of the equipment. When performing a financial analysis to determine if equipment should be procured, depreciation can be important however. This is due to the effect that it has on income taxes.

Before looking at just what effect depreciation has on income taxes, the depreciation schedule needs to be determined. While there a number of depreciation methods, straight-line depreciation is required by current tax law for assets with long lives. Straight-line depreciation is the capital cost less the salvage value (if any), divided by the economic life or:

$$d_{SL} = (C - SV)/n \qquad (3.35)$$

where d is the annual depreciation, C is the capital cost, SV is the salvage value and n is the number of years in the economic life. For simplicity, assume that a chiller costs $12,000, will be used for five years and it is expected that it can be sold at that time for $2000, the salvage value. The annual depreciation rate is:

$$d_{SL} = (\$12,000 - \$2000)/5 \qquad (3.36)$$

$$d_{SL} = \$2000 \qquad (3.37)$$

Placed into a depreciation schedule it would appear as:

Table 3.2 Depreciation Schedule

Year n	Depreciation Expense During Year n	Book Value at End of Year n
0	0	$12,000
1	$2,000	$10,000
2	$2,000	$8,000
3	$2,000	$6,000
4	$2,000	$4,000
5	$2,000	$2,000

All for profit business entities must pay income taxes. Income is defined as being equal to revenues for the period less the expenses for the same period. Assuming that the firm's income is from normal operations where no investments are made, it is possible to calculate the pre-tax income by subtracting expenses from revenues. By applying the

41

income tax rate, the net income to the period is determined. Another way to determine the net income is to apply the tax rate to both the revenues and expenses to get revenues and expenses after taxes. These can then be subtracted to give the income after taxes. By doing this, it shows that at an income tax rate of 30 percent, for each dollar of income, the firm would keep $1(100% - 30%) = $.70. On the other hand, for each dollar the firm spent, 30 cents would be provided by the government.

If the entity paid no taxes, such as the government itself, depreciation would have no effect in present value analysis. However, because it is possible to reduce the entity's annual expense by the current tax rate on the depreciation expense; income taxes should not be ignored in the analysis for entities subject to income taxes. Repeating the pump example above, assuming an incremental income tax rate of 40 percent (the current incremental tax rate is 39.5 percent), neglecting state taxes, and using straight-line depreciation, *the cash flows for the previous example now are shown in Figure 3.3.*
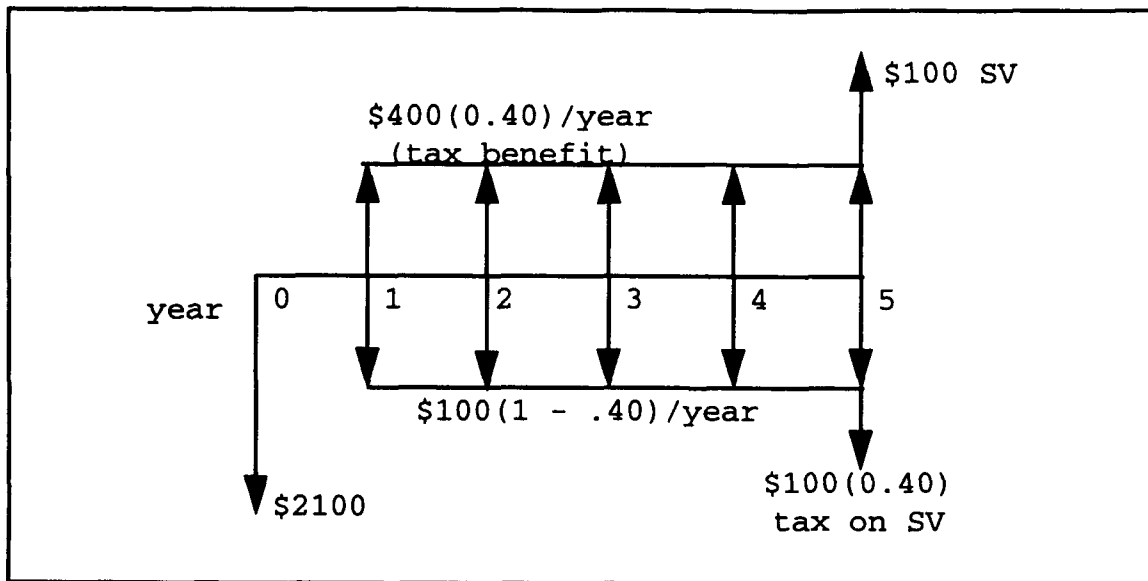
Figure 3.3 Cash Flow for Present Value Analysis with Taxes

Present value can now be calculated:

$$P = -\$2100 - (1 - 0.40)(\$100)(P/A,7,5) + 0.40(\$400)(P/A,7,5) \tag{3.38}$$

$$+ \$100(P/F,7,5) - 0.40(\$100)(P/F,7,5)$$

$$P = -\$2100 - 0.60(\$100)(4.1002) + 0.40(\$400)(4.1002) \tag{3.39}$$

$$+ \$100(0.7130) - \$40(.7130)$$

$$P = -\$2,100 - \$246.01 + 656.03 + \$71.30 - \$28.52 \tag{3.40}$$

$$P = -\$1,647.20 \tag{3.41}$$

43

Due to the tax savings generated by the depreciation and annual operation and maintenance costs, the present value of the cost of operating the pump has decreased from -$2,438.72 to -$1,647.20 or by $791.52.

When preparing to make an investment in an asset, it is essential to know the period over which the investment will be used. One firm may have the intention of disposing of a piece of equipment after three years while another may hold onto it for a longer (or shorter) period. For some assets, particularly those with long lives, it may be very difficult to estimate the life with any accuracy. New technology may become available or, in the case of chillers, new legislation may go into effect which makes replacement desirable. These can change the original estimate. In any case, an effort must be made to determine the economic life given the known conditions. Economic life is defined as the number of years that a capital expenditure will make a positive economic contribution to the owner. Economic life may be reached if the asset shows wear or deterioration, another asset has been developed that can perform the same job at a lower economic cost, the asset is no longer required, or changes in law occur. Economic service life is used as the life of the equipment in depreciation calculations (Salvendy, 1982:9.3.1).

GAAP (required by the Securities and Exchange Commission for publicly traded companies) allows the owner of the asset to determine the depreciation method and the cost is spread over its economic life. This is not so for depreciation for tax purposes. Here, the number of years to use and the method of depreciation is dictated by tax law. The government, by taking this action, can help encourage or discourage capital investment by changing the rate at which organizations are able to receive tax benefits on their investments.

The basics of the current tax law were established with the Economic Recovery Tax Act of 1981. This established the Accelerated Cost Recovery System (ACRS) which applied to assets purchased in 1981 through 1986 (Kieso, 1992:557). The Tax Reform Act of 1986 modified ACRS and established the Modified Accelerated Cost Recovery System (MACRS). It applies to depreciable assets acquired in 1987 and later. In MACRS, each depreciable asset is assigned to a property class that dictates the depreciable life of the asset. In addition, the property class to which the asset is assigned also establishes the depreciation method that will be used (Kieso, 1992:557,558).

The Tax Reform Act also requires that a salvage value of zero be used for tax purposes. In addition, for assets other than real property or where "substantial property" is placed in service during the last three months of the year, all property is assumed to be placed into service or disposed of at the midpoint of the tax year (United States Congress, 1986:100 Stat.212-2123).

Chillers, are an integral part of the buildings which they serve. As such, they are deemed part of the building and are depreciated at the same rate and by the same method as the building. Under the current tax law, the Tax Reconciliation Act of 1993, the depreciation period is 39 years using the straight-line depreciation method (Burns, 1994).

Replacement Analysis

Life cycle cost analysis looks at the total projected costs for a project over its intended life. By applying present value methods, these can be summarized as one total cost. Often, if one is looking at a new investment, the life cycle costs of several alternatives are

evaluated. These can then be compared, and the alternative with the lowest life cycle cost selected. For instance, this method might be used when deciding which of two different chillers a firm should buy. The only requirement is that the interest rate used in the calculation and the life of each alternative be identical.

When looking at when to replace an existing piece of equipment with a piece of new equipment, the lives will generally not be equal. Taking two identical chillers, one 20 years older than the other, the newer chiller will clearly outlast the other. A difference in economic lives exists. In addition, other differences exist. These are in the cash flow streams for the equipment being compared. The older existing equipment has no purchase price (any transactions before the evaluation cannot be reversed or undone, therefore they are "sunk" costs) but it may have high operation costs. Conversely, there is a procurement cost for new equipment. However, operation costs will usually be less than those for existing equipment (Salvendy, 1992:9.4.15).

Replacement analysis recognizes these differences and provides two different methods for evaluation. The first method is referred to as Evaluation of Replacements Involving Sunk Costs, the second as Replacement Analysis Based on Economic Life (Fabrycky, 1974:128,137).

Evaluation of Replacements Involving Sunk Costs.

Replacement analysis requires the introduction two new terms, "defender" and "challenger." The "defender" is the equipment that is currently in place. In effect, it is defending its right to remain in place. The "challenger" is the asset that is being proposed as a replacement (Salvendy,1992:9.4.15).

Using evaluation of replacements involving sunk costs, one must know the salvage value of the equipment if sold at the present time. Depreciation is a value assigned for accounting purposes and may not reflect the value that the market would pay for the equipment. For example, suppose that one paid $4,000 for a piece of equipment six years ago. At that time, it was estimated that the equipment had a life of 10 years. Now the defender, Machine A, its operation costs are $2,000 per year, increasing by $900 each year with an estimated $100 salvage value in four years. Its book value, (cost less depreciation) is $1,660 ($4,000 - 6(3,900/10)). An alternate machine, the challenger Machine B, is available that will cost $3,500 and has an estimated operation cost of $1,000 per year increasing by $400 each year over its seven year life. The salvage value is $100. The salesman is prepared to pay $1,000 for the Machine A. No higher price can be found. What action should be taken?

To perform the analysis, one takes the approach of an outsider looking to purchase either one or the other piece of equipment. Therefore, the sunk cost of $3,000 ($4,000 - $1,000), for Machine A is ignored. The firm uses an interest rate of 15 percent. Therefore, the initial cost of Machine A is $1,000 and the initial cost of Machine B is $3,500. Neglecting depreciation and taxes, the cash flows for both pieces of equipment are shown in Figures 3.4 and 3.5.
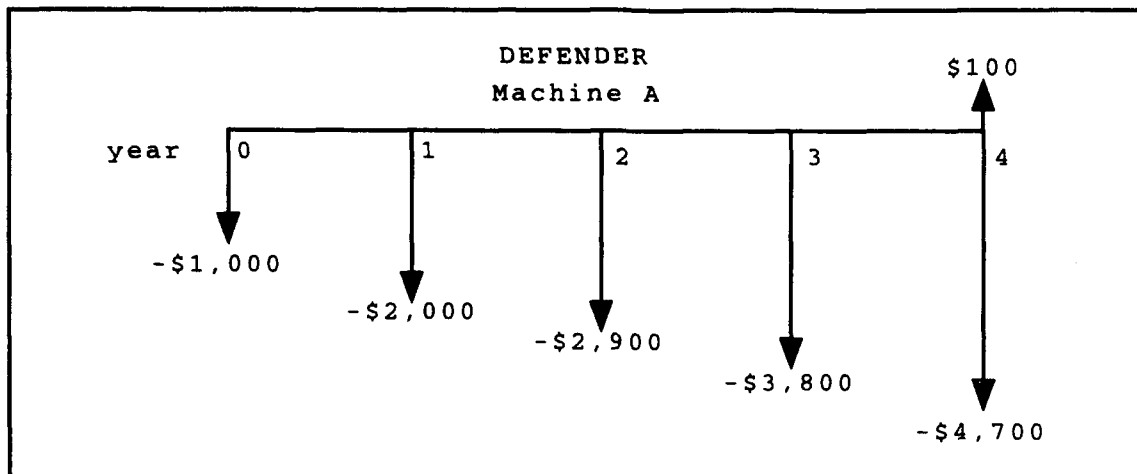
Figure 3.4 Cash Flow for Defender
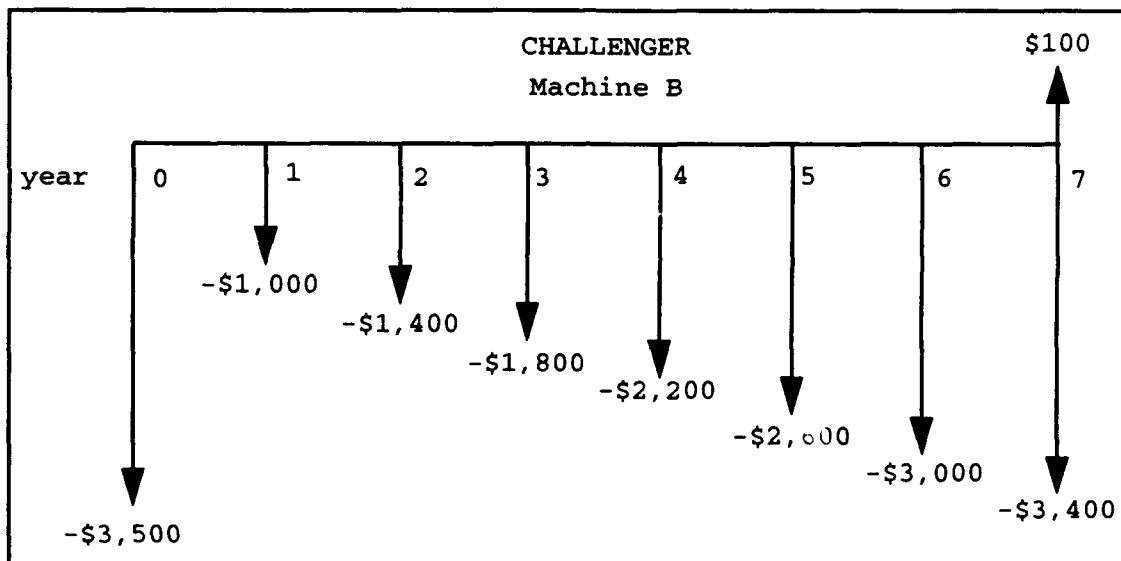
Figure 3.5 Cash Flow for Challenger

Instead of calculating the present value of the alternatives, replacement analysis calculates the equivalent annual cost. This is the conversion of all cash flows into an equal cost for each period over the life of the equipment (Fabrycky, 1974:98). Equivalent annual cost (EAC) is the sum of the annual capital recovery with return (CR) and the annual operating cost (OC). Or:

$$EAC = CR + OC \qquad (3.42)$$

Where CR is:

$$CR = P(A/P,i,n) - F(A/F,i,n). \qquad (3.43)$$

But since $\quad (A/F,i,n) = (A/P,i,n) - i \qquad (3.44)$

$$CR = P(A/P,i,n) - F[(A/P,i,n) - i] \qquad (3.45)$$

$$CR. = (P - F)(A/P,i,n) + Fi \qquad (3.46)$$

Since in this example, OC is not equal from year to year, it can be annualized using the uniform-gradient series, or the cash flows can be taken to the present value and annualized using the capital recovery factor. The equivalent annual costs calculated for Machine A and Machine B are shown in Table 3.3.

By changing to Machine B, there will be a savings of \$3,524 - \$2,812 = \$712 each year for the next four years. For the years after that, any savings will be dependent on the economic characteristics of the alternate machine evaluated at that time (Fabrycky, 1974:128-130).

Table 3.3 Comparison of Replacement Analysis

Involving Sunk Costs for Machines A and B

Machine A

$$CR = (\$1,000 - \$100)\overset{(A/P,15,7)}{(0.3503)} + (\$100)(0.15) \qquad \$330$$

$$OC = \$2,000 + \$900\overset{(A/G,15,7)}{(1.3263)} \qquad \underline{\$3,194}$$

$$\underline{\underline{\$3,524}}$$

Machine B

$$CR = (\$3,500 - \$100)\overset{(A/P,15,7)}{(0.2404)} + (\$100)(0.15) \qquad \$832$$

$$OC = \$1,000 + \$400\overset{(A/G,15,7)}{(2.4499)} \qquad \underline{\$1,980}$$

$$\underline{\underline{\$2,812}}$$

Replacement Analysis Based on Economic Life.

The second method is replacement analysis based on economic life. Economic life is defined as the number of years that a capital expenditure will make a positive economic contribution to the owner. Economic life may be reached if the asset shows wear or deterioration, another asset has been developed that can perform the same job at a lower economic cost, the asset is no longer required, or changes in law occur (Salvendy, 1982:9.3.1). This life is different from the service life of an asset. The service life is the actual time that the asset is in place regardless of whether it is making a positive contribution to the owner.

Using this method, there are two important differences from the previous method. Because the economic life of the asset is calculated rather than assumed, the market value of the asset must be known at the end of each year. This may be lower or higher than the value at which the asset is carried on the firm's books. Second, this calculation is a continuous iteration until the solution is found. As a result, salvage value is not included. Although the impact is usually negligible; in many instances, this is not the case. Using the example above the economic life of the defender is calculated in Table 3.4.

Table 3.4 Replacement Analysis Based on Economic Life - Defender

DEFENDER
Interest Rate   15%
Initial Value at Time of Evaluation $1,000

A End of Year n	B Salvage Value When Asset Retired at Year n	C Operation and Maintenance Costs During Year n	D Initial Value at Start of Analysis Less Salvage Value (3000 - B)	E Capital Recovery Factor for Year n (A/P,i,n)	F Annual Equivalent Costs of Capital Asset When Retired at Year n (D X E) + (B X i)	G Uniform - Gradient Series Factor for Year n	H Annual Equivalent Cost of Operating for n Years (1000 + 700(A/G,i,n))	I Total Annual Equivalent Cost When Asset Retired at Year n (F + H)
1	$750	$2,000	$2,750	1.1500	$3,275	0.0000	$2,000	$5,275
2	$500	$2,900	$3,000	0.6151	$1,920	0.4651	$2,419	$4,339
3	$300	$3,800	$3,200	0.4380	$1,447	0.9071	$2,816	$4,263
4	$100	$4,700	$3,400	0.3503	$1,206	1.3263	$3,194	$4,400
5	$0	$5,600	$3,500	0.2983	$1,044	1.7228	$3,551	$4,595

Indicates point where equipment is at its Economic Life

Table 3.5 Replacement Analysis Based on Economic Life - Challenger

CHALLENGER
Interest Rate   15%
Initial Value at Time of Evaluation $3,500

A End of Year n	B Salvage Value When Asset Retired at Year n	C Operation and Maintenance Costs During Year n	D Initial Value at Start of Analysis Less Salvage Value (3000 - B)	E Capital Recovery Factor for Year n (A/P,i,n)	F Annual Equivalent Costs of Capital Asset When Retired at Year n (D X E) + (B X i)	G Uniform - Gradient Series Factor for year n	H Annual Equivalent Cost of Operating for n Years (1000 + 400(A/G,i,n))	I Total Annual Equivalent Cost When Asset Retired at Year n (F + H)
1	$2,000	$1,000	$1,500	1.1500	$2,025	0.0000	$1,000	$3,025
2	$1,500	$1,400	$2,000	0.6151	$1,455	0.4651	$1,186	$2,641
3	$1,000	$1,800	$2,500	0.438	$1,245	0.9071	$1,363	$2,608
4	$750	$2,200	$2,750	0.3503	$1,076	1.3263	$1,531	$2,606
5	$500	$2,600	$3,000	0.2983	$970	1.7228	$1,689	$2,659
6	$250	$3,000	$3,250	0.2642	$896	2.0972	$1,839	$2,735
7	$100	$3,400	$3,400	0.2404	$832	2.4499	$1,980	$2,812
8	$0	$3,800	$3,500	0.2229	$780	2.7813	$2,113	$2,893

Indicates point where equipment is at its Economic Life

Based on the results in the table, the defender would have to be kept three additional years to reach the economic life. At this point, the total equivalent annual cost would be $4,254. However, by replacing it with the challenger, and operating it for three years, the equivalent annual cost can be reduced to $2,578 for an annual savings of $1,676.

While the examples above considered operation and maintenance costs in addition to capital cost, for a complete analysis, other factors need to be included. Among these are declining efficiency, and obsolescence (Fabrycky, 1974: 146-144).

Approach

Many chillers may need to be replaced as refrigerants become more scarce and their costs increase. As CFC's go out of production, firms will be faced with the problem of determining the optimal time to make their chiller replacement. The model developed here is intended to provide chiller users with a tool that can be used to assist them in making the replacement decision. In developing this model several assumptions are made.

Number of Chillers.

Many different types of businesses use chillers to meet their air conditioning needs. Some applications are in office buildings, hotels, schools, and factories. The firm may have one chiller to serve its needs or several connected in parallel, some of which can be shut down as the heat load changes. Further, some organizations may have only one chiller per building but have a number of different buildings which require chillers.

The model assumes that a single chiller is owned by the organization. If the chiller is replaced, the firm is may sell the CFC refrigerant that has been recovered from the existing unit. If the decision is made to retain ownership of the refrigerant, either as a source for other chillers or simply as an investment, the value of the refrigerant is the current market price.

Capacity.

Cooling loads may change over time as the use or occupancy of buildings change or as new technologies are developed. One example is an office building where 10 to 15 years ago computers, large heat generators, were located in the firm's computer center. Now, with the proliferation of personal computers, they may be located throughout the building, generating heat in areas not designed to handle the load. The model assumes that the existing chiller is adequate to meet the current cooling load and that any replacement will be of the same capacity.

Value of Existing Chiller.

The value of the existing chiller can only be determined by the market. For an existing chiller three possible markets exist: the used chiller market, the scrap market, and finally cannibalizing the chiller to use for replacement parts on other chillers of the same size, type, and manufacturer (Zadow, 1994). The last option is not considered in the model because the value of the parts is dependent on the need for the part, availability of new parts, etc.

Some firms purchase used chillers, then resell or rent them. Others purchase the chillers, convert them to use a non-CFC refrigerant, such as HCFC-123, and then resell or rent

55

them. In both cases, these markets prefer chillers built after 1980. Chillers built before this date use heat exchangers, drive-trains, and compressors designed before the 1970's "energy crisis." In both these cases, the value of the chiller is a function of age and condition (Trane Company, 1994:2; Zadow, 1994).

The final alternative is the scrap market. This is the primary option taken in disposing of pre-energy crisis design chillers. It may also be used for more recent chillers should an immediate buyer not be identified at the time of chiller replacement (Blakely, 1994; Zadow, 1994). The model assumes that the scrap market is used to determine the current value of the existing chiller and that both the existing and replacement chiller will be disposed of through this market.

Taxes.

While the effect of taxes can be integrated into the model, the objective here is to look at chiller replacement from an Air Force point of view. Since the Air Force pays no taxes, that part of the calculation is not included. For application in the private sector, it should be considered, with information on depreciation rate of the existing chiller coming from a firm's accounting department when a particular chiller is being studied.

Model Design

To develop the optimization model, the life cycle cost of the chiller to be replaced, the defender, must be compared to the life cycle cost of the replacement chiller, the challenger. Because this is a replacement analysis problem, the equivalent annual costs of the defender and challenger are compared. Since the model looks ahead to determine

the optimal time to make the replacement, the factor of time must be included in the calculation.

While this model will optimize when in time to replace the existing chiller, additional uncertainties may enter the calculation. One example is the future price of CFC's. While some have attempted to predict the future price of refrigerants, what in fact happens as the phase out date approaches is unknown. Prices may follow some of these predictions, or even decline as more firms move to non-CFC refrigerants and demand falls off. On the other hand, the change to alternative refrigerants may be delayed either due to company policy or funding or due to a lack of chiller production capacity. Users may continue to require the CFC which is no longer in production. This may increase prices well beyond those that are predicted. Demand may be such that spot markets, similar to those in the oil industry, are created.

Due to the differences in the replacement analysis techniques, it is possible to either take the approach that the chiller has a known life and a salvage value at the end of that life, or to assume that the value of the chiller is known at the end of each year throughout its life. While the value of older chillers can be estimated for each year, this is not easily done for newer chillers. At the present time, information is available on the salvage value of chillers and on the cost of new chillers. Based on this, evaluation of replacements involving sunk costs methods will minimize the number of unknowns.

By selecting this method, the analysis is conducted for the existing chiller to remain in operation from one additional year to the number of years that represents the chiller reaching its service life. This is done so that each point includes the salvage value of the

chiller at the point in time when it may be removed from service due to the challenger. In each case, the equivalent annual cost representing the initial value, the final value, operation and maintenance costs is calculated. Thus EAC_{yr0-1}, EAC_{yr0-2}, ..., EAC_{yr0-n} is calculated where 0 is the beginning of the first year and n is the end of the last year of the chiller's service life. Equivalent annual cost for each calculation is:

$$EAC = CR_{procurement\ and\ disposal} \qquad (3.47)$$
$$+ CR_{refrigerant}$$
$$+ OC_{annual\ O\&M\ cost}$$
$$+ OC_{non-annual\ maint}$$

where

$$CR_{proc\ and\ disposal} = (PC-SV)(A/P,i,n) + SV(i) \qquad (3.48)$$

$$CR_{refrigerant} = \{\Sigma(ref_{0-n}(P/F,i,n)\}(A/P,i,n) \qquad (3.49)$$

$$OC_{annual\ O\&M} = operation\ labor\ cost \qquad (3.50)$$
$$+ maint\ labor\ cost + parts\ cost$$

$$OC_{non-annual\ maint} = (non-annual\ parts \qquad (3.51)$$
$$+ non-annual\ labor)(P/F,i,n)(A/P,i,n)$$

Procurement and Disposal Costs.

The procurement cost of the existing chiller is the scrap value discussed above. For the replacement chiller, the procurement cost is the cost of the chiller, including refrigerant, and the cost to install it. Disposal costs in both cases are the scrap value of the chillers.

Refrigerant Cost.

Chillers are built in two basic configurations, low pressure and high pressure chillers. For low pressure chillers, while operating, the pressure of the refrigerant in the evaporator is less than atmospheric pressure. For these chillers it is possible for air to leak into the system. Air is removed from the chiller using a purge unit. While removing air, purge units also remove a small quantity of refrigerant. In high pressure chillers, pressures are greater than atmospheric throughout the chiller. Here it is possible for refrigerant to leak out of the chiller. In both cases, additional refrigerant must be added to the system periodically to keep the chiller operating efficiently.

Operation and Maintenance Costs.

Operation costs are the cost of electricity required to turn the compressor motor and the cost of labor to monitor the chiller. The quantity of electricity required depends on the capacity of the chiller, the rate of power consumption, and the number of hours the chiller is operated per year. The rate of power consumption (kW/ton) is a function of heat transfer, refrigerant thermodynamics (cycle efficiency), drive-train efficiency (efficiency of the transfer of electrical to mechanical energy), and compressible fluid dynamics (compressor efficiency) (Trane Company, 1994:2).

Maintenance costs are composed of the cost of annual maintenance and the cost of maintenance that is performed on a chiller after it has been in service for a number of years or has run for a number of hours. Annual maintenance consists primarily of changing oil and oil filters, and shutting down and preparing chillers to be restarted should they operate for only a portion of the year. Annual maintenance also includes replacing any refrigerant that is lost.

Maintenance that is done on a non-annual basis includes the periodic teardown of the chiller to inspect the rotating components. These include the drive train and compressor impeller. In addition, the bearings supporting these components are also inspected and replaced if sufficient wear is evident.

Running the Model.

For the existing chiller, the model is run where n = 1,2,3,.... In each case, the result is the cost to procure, operate, and dispose of the system after being in operation for that number of years. These points can be plotted to create a curve representing the current equivalent annual cost to operate the chiller for up to n years in the future.

A cost curve can also be generated for a replacement chiller. This will be the current equivalent annual cost to purchase, operate, and dispose of the chiller over its service life. It can also be calculated using the same equations. Here n is equal to the service life of the replacement chiller. Because actual replacement may occur in the future, the impact of the cost of replacement changes due to the time value of money. To provide a measure

of the current impact, the current result is discounted into the future. This is not required however if the comparison is made using constant dollars.

The two cost curves are plotted together in Figure 3.6. The figure shows that if the existing chiller is operated until time T_1 the equivalent annual cost C_{E1} will be less than the equivalent annual cost of purchasing and operating a replacement chiller C_{R1}. Similarly, if the existing chiller is operated until time T_2, the equivalent annual cost of operation C_{E2}, has exceeded that of installing a replacement chiller C_{R2}. The point at which the replacement should be made is the break-even point, T_{BE}. Here the cost of operating the existing chiller or replacing it with a new chiller is identical, C_{BE}. Because a finite chiller life is assumed, the existing chiller must be replaced on reaching the end of its service life. This is true even though the equivalent annual cost of the existing chiller might still remain below that of the replacement chiller.
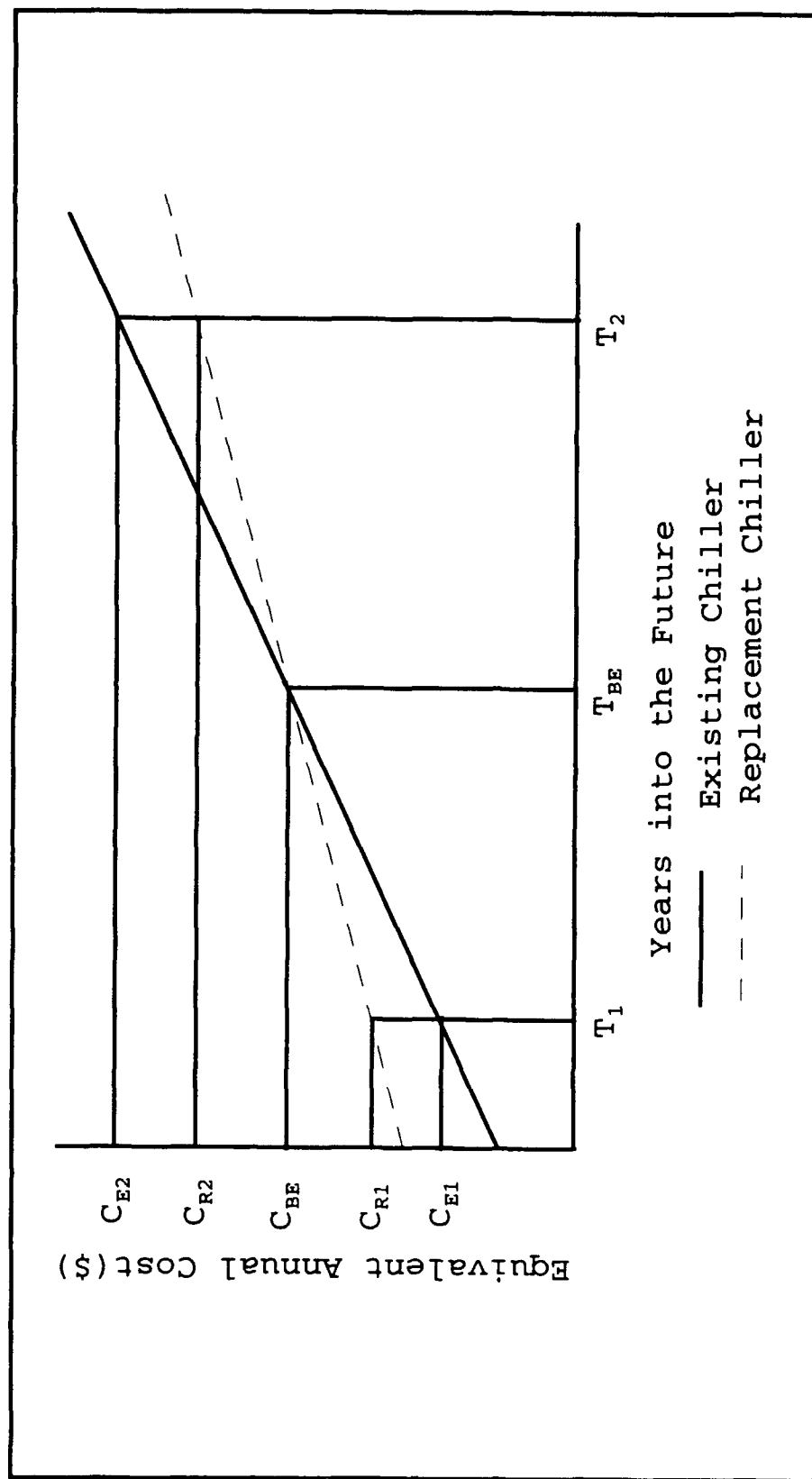
Figure 3.6 Chiller Cost Comparison

62

Chapter Four - Sample Model Application

Using the model presented in the previous chapter, a validation can now be performed.

Before doing so however, the specific inputs to the model are described. Many of these

inputs are situation dependent. A user of the model should input values reflecting the

chiᵢ. being considered for replacement along with other data that may be more relevant

to the situation being investigated. The results of the calculations used in this example

are presented following the description of the inputs.

Inputs to the Model

Capacity.

Centrifugal chillers are available in a range of capacities. York International markets

chillers that have capacities from 100 to 8,500 tons (York International, 1993:6). For this

example a capacity of 300 tons was chosen. This is typical of the size of centrifugal

chillers used at Wright-Patterson AFB (McKay, 1994). The user should input the

capacity of the chiller being evaluated for replacement.

Refrigerant.

At the present time, the major refrigerants being phased out are CFC-11 and CFC-12.

The Trane Company which manufactures low pressure centrifugal chillers (which use

CFC-11) has between 25% and 50% of the overall chiller market (Scheckie, 1994). The

remainder of the market is split between Carrier Corporation, SnyderGeneral Corp., and

York International Corp. Of the remaining companies, only York International produces

low pressure chillers (CRWC, 1994:3-7). This example will assume that CFC-11 is the refrigerant used in the chiller to be replaced. While CFC-12 might be chosen as the refrigerant in the existing chiller, its current commercial price is within 10% of the price for CFC-11. Given the minimal price difference, the model could also be used when evaluating a high pressure chiller for replacement. HCFC-123, used in low pressure chillers, is assumed as the replacement refrigerant.

Value of the Existing and Replacement Chillers.

Equipment.

For this example, the current value of the existing chiller equipment is determined by the scrap market. Presently, a central Ohio scrap dealer will pay $0.027 per pound for a chiller that is delivered to their scrap yard. While chillers contain many metals which normally could be sold to a dealer for a higher price, this low value is a result of the need for the dealer to dismantle the chiller to gain access to those items (Miller, 1994; Blakely, 1994). A 300 ton chiller weighs approximately 14,300 lbs (Rapier, 1994). This makes it worth $386 (see Appendix D).

For those applying the model, the local scrap market should be checked to determine what dealers will pay for the chiller. An alternate source would be to contact mechanical contractors who install chillers and may often be required to dispose of used chillers. Any removal and transportation costs involved should be factored in. Finally, if the user has recent experience with the used chiller market or is able to get an estimate on the value of the chiller being considered for replacement that value may be used as the current value.

64

The salvage values for the existing and replacement chillers are also determined by the scrap market. In the long run, no change of the price of scrap is assumed. If sale to the used chiller market is anticipated, the value of the chiller for each year from the present time until the end of the chiller's service life is required.

For new chillers presently on the market in the 100 to 500 ton capacity range, the estimated cost is $250 per ton. Using this figure, a 300 ton chiller would cost $75,000 (Tuchnowski, 1994). For those applying the model to a specific situation, a market survey of the manufacturers in the user's local area should be performed for the specific size chiller to be replaced.

Refrigerant.

At the present time, used CFC-11 and CFC-12 can be sold to a reclaimer/recycler for $2.50 to $3.00 per pound. It can be purchased for $7.00 per pound (Elkins, 1994). The current cost of virgin CFC-11 and CFC-12 is $9.75 in commercial quantities (Wilson, 1994). As supplies of virgin CFC's become more scarce, the market will drive the price of reclaimed refrigerant closer to that of unused refrigerant. It is assumed that the cost of reclaimed refrigerant will become equal to the cost of virgin refrigerant during the next year as manufacturers shut down production plants. At that point the prices will follow those shown in Appendix D which are based on cost projections for refrigerrants done by James Calm and published in the May 1992 issue of Heating/Piping/Air Conditioning. It is further assumed that the price a recycler will pay for refrigerant in the future will be $3.00/$7.00 or about 40% of the sales price. See Appendix D for calculations and sources of information.

A user of the model should keep abreast of the local availability and prices of the refrigerant that the existing chiller uses. Future changes in the market should be incorporated into any calculations made.

New chillers are normally supplied with the first charge of refrigerant since they undergo functional testing before being shipped from the factory. As a result, there is no cost for the initial refrigerant in an existing chiller. The cost of any make up refrigerant is included in Appendix D.

Chiller Age and Life.

The example assumes that the current age of the chiller being considered for replacement is 15 years. The service life used is 30 years. This is supported by The Trane Company and SnyderGeneral who both design their chillers to last for 25 to 30 years (Flaherty, Kenneth, 1994; Rapier, 1994). This also generally corresponds with the age of the older chillers at Wright-Patterson AFB, Area B.

Power Consumption and Cost.

The power consumption used for the existing chiller in the example is 0.83 kW/ton. This was taken from a 15 year old chiller recently replaced at Wright-Patterson AFB. A user should enter the power consumption of the chiller that is being considered for replacement.

For replacement chillers, the example used a rate of 0.65 kW/ton. This is the typical power consumption for new chillers on the market (Tuchnowski, 1994). A user of the

66

model should be aware that there can be a wide variability in the power consumption of new chillers. The Trane Company presently has more than 200 centrifugal chiller configurations that have a capacity of 400 tons. These have power consumptions about 0.70 kW/ton to 0.53 kW/ton (Rapier, 1994). When running the model, the expected power consumption should be used. One source is the value used in the engineering specifications of the replacement chiller.

The incremental cost of electricity in the Dayton OH area for an industrial user is $0.02111 per kW-hr (Wenzlick, 1994). A user should input information applicable to the area where his operation is located.

Operation and Maintenance.

Most existing chillers have the capability to be started and stopped remotely through a computer system. If not, it is also possible for then to be started and stopped using electric timers (McKay, 1994). When computer systems are used, they are also capable of monitoring the operation of the chiller as well as other air conditioning system components, such as air handlers, pumps, and cooling towers, to see that they all operate within pre-established norms. Should normal limits be exceeded, warning alarms are sounded informing the operator of the problem. Because a single operator is able to monitor a wide variety of equipment, the time spent monitoring the chiller is difficult to calculate. In addition, should the chiller to be replaced not be there, the operator would still need to monitor other chillers and pieces of equipment. Therefore, the labor time required to monitor any single chiller is assumed to be zero.

One expects that as equipment ages, the cost of maintenance will increase. Attempts were made to get specific data regarding the maintenance cost of chillers as they age from Wright-Patterson AFB and Newark AFB. In both cases however, time and costs were tracked against the total HVAC systems for an area or the entire base.

Manufacturers were contacted to attempt to get similar information. While they had information on scheduled maintenance, they did not or could not produce information related to additional service required due to age. The Trane Co., the major manufacturer of low pressure chillers, stated that they recommended that a major overhaul/inspection be performed every 12,000 hours. The estimated time required was 200 man-hours. No estimate was provided on the cost of parts required (Rapier, 1994). In addition, they recommend that every 50,000 hours the bearings and gaskets be replaced. Estimated cost of bearings and gaskets was $2,000 (Komarek, 1994). Finally, they estimated that 40 hours would be required to perform annual maintenance. For this maintenance they estimated that the cost of parts was $100 (Rapier,1994). These estimates were used in the example.

Stoffel Equipment Co. is a distributor for SnyderGeneral. They charge $72 per hour to service centrifugal chillers (Flaherty, Kent, 1994).

A user of the model should strive to get as much operation and maintenance information on the specific chiller to be replaced as possible. Through this and general maintenance policy, the cost and frequency of operation and maintenance can be determined. Should service be performed by a contractor, the contract itself may contain this information.

Run Time.

For the example a run time of 5 days per week, 24 hours per day, from 1 June to 15 October, the cooling season at Wright-Patterson AFB was used. At this rate, chillers operate 2,280 hours per year (McKay, 1994). Users should supply information on their own expected run times for the chiller to be replaced.

Interest Rate.

With exception of the cost of refrigerants, all calculations were performed in 1994 dollars. The cost of refrigerants, due to continued demand for CFC's as well as increasing capacity to supply non-CFC refrigerants, are more volatile than the cost of other factors such as electricity, parts and labor. The tables previously discussed are the source for refrigerant costs. A discount rate of 7% is used in the analysis. The user should use the discount rate applicable to his own organization.

Calculation Results

Using the inputs described above, the cost of operating a 15 year old, 300 ton chiller, for 2,280 hours per year and a power requirement of 0.83 kW/ton was calculated. Because the calculation looked for the point where the existing chiller should be replaced, the calculation looked at the equivalent annual cost to operate the chiller if it were replaced in each of the following years until the chiller reached the end of its service life.

At the same time a calculation was performed to determine the equivalent annual cost of purchasing and operating a new chiller for a 30 year service life (the same service life

used with the existing chiller). Calculations are shown for the existing and replacement chiller in Appendix E.

Based on the calculations performed, the plot in Figure 4.1 can be drawn. The plot assumes that the existing chiller will operate for at least one additional year. The numbers used in the plot are shown in Table 4.1. This plot shows that the equivalent annual cost to operate the existing chiller one additional year is $15,389. If it is replaced at that time, the equivalent annual cost to operate the new chiller for 30 years will be $20,892. To operate the existing chiller for two years will increase the equivalent annual cost to $22,961, greater than the cost to operate the replacement chiller. In future years, the equivalent annual cost of operation drops below that of the replacement chiller. The peak in the second year is due to the cost of the scheduled non-annual maintenance of the chiller. The model indicates then, that should the existing chiller be operated for less than three years, it should be replaced. If operation for three or more years is expected, it should remain in place.
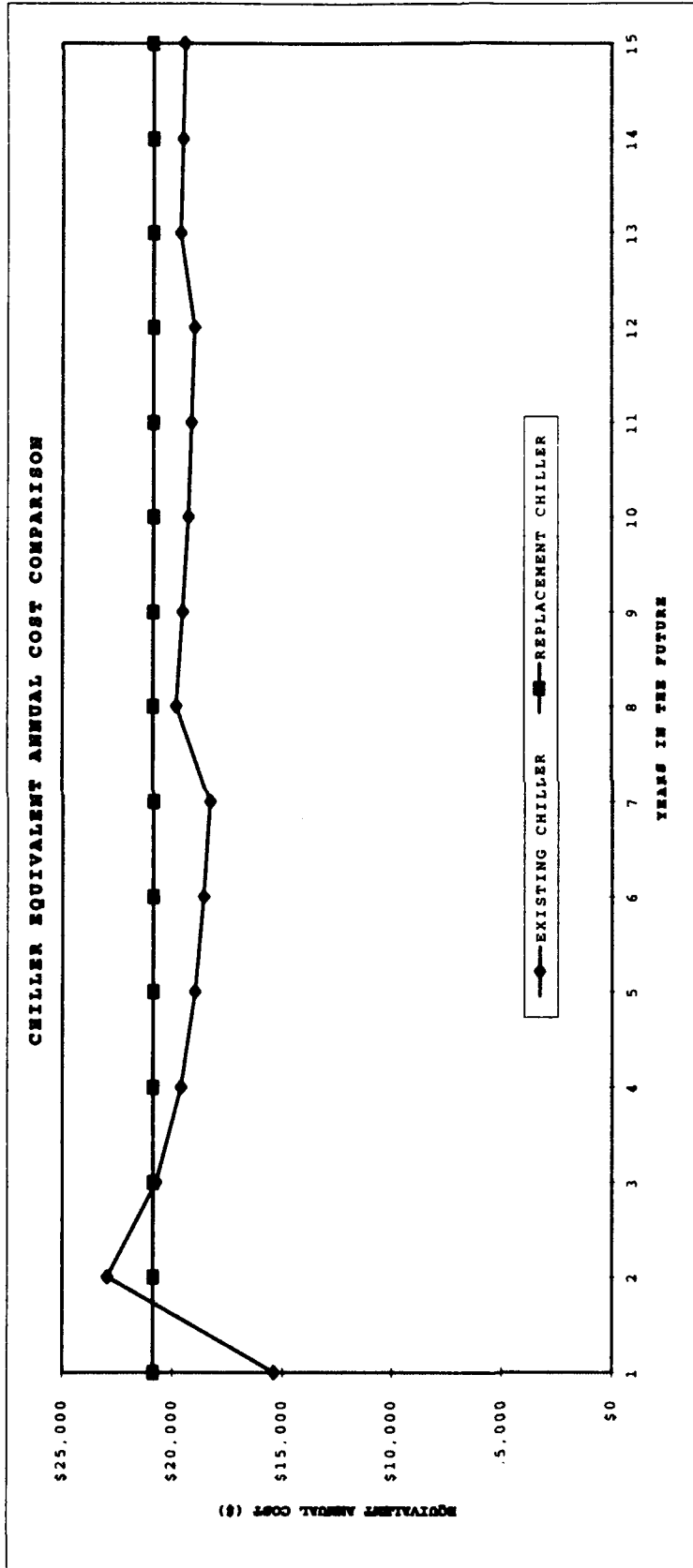
CHILLER EQUIVALENT ANNUAL COST COMPARISON

EQUIVALENT ANNUAL COST ($)

$25,000
$20,000
$15,000
$10,000
$5,000
$0

YEARS IN THE FUTURE

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

EXISTING CHILLER   REPLACEMENT CHILLER

	Existing	Replacement
Chiller Capacity	300 tons	300 tons
Power Consumpton	0.83 kW/ton	0.65 kW/ton
Run Time	2280 hrs/year	2280 hrs/year

Figure 4.1 Chiller Equivalent Annual Cost Comparison

Table 4.1 Data for Chiller Equivalent Annual Cost Comparison

	Existing	Replacement
Chiller Capacity	300 tons	300 tons
Power Requirement	0.83 kW/ton	0.65 kW/ton
Run Time	2280 hrs/year	2280 hrs/year

YEAR	EXISTING CHILLER	REPLACEMENT CHILLER
1	$15,389	$20,892
2	$22,961	$20,892
3	$20,720	$20,892
4	$19,611	$20,892
5	$18,980	$20,892
6	$18,566	$20,892
7	$18,291	$20,892
8	$19,805	$20,892
9	$19,521	$20,892
10	$19,302	$20,892
11	$19,133	$20,892
12	$18,999	$20,892
13	$19,657	$20,892
14	$19,537	$20,892
15	$19,439	$20,892

72

However, chiller owners may have different size chiller equipment, which may or may not require as much power, or experience the same run time per year. Figures 4.2 through 4.7 show the impact of varying one of these parameters while holding the other two constant. Figures 4.2 and 4.3 show the same calculation for a 100 ton and 500 ton chiller respectively. From looking at the figures, one sees an unexpected result. One might think that replacement of a larger chiller would be preferred over a smaller one. However, the figures show the opposite. This may be due to the fact that the cost of the replacement chillers was taken at $250 per ton. Clearly, even within this family of chillers some efficiencies of scale come into play. Because these are not reflected in the calculations, one would expect the cost of the larger chiller to be higher than it might be in practice. The model does show however, that the impact of maintenance costs is more clearly pronounced for the 100 ton chiller than for the 500 ton chiller. Since the effects of non-annual maintenance quickly blend into the curve for the 500 ton chiller, the major costs must be that of electricity and annual maintenance.

A comparison of Figure 4.1, 4.4 and 4.5 shows the impact of power consumption on chiller operation. Looking at the equivalent annual cost to operate the existing chiller for 15 years (at this point, the curve is smoother because the cost of non-annual maintenance is distributed over the 15 year period), the cost of the 0.65 kW/ton unit is $17,000 to $18,000 per year while the cost of the 0.90 kW/ton unit is about $21,000 per year. Looking at a shorter time frame, the 0.65 kW/ton unit never reaches the curve for the replacement unit.

73

CHILLER EQUIVALENT ANNUAL COST COMPARISON

EQUIVALENT ANNUAL COST ($)

$16,000
$14,000
$12,000
$10,000
$8,000
$6,000
$4,000
$2,000
$0

YEARS IN THE FUTURE

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

EXISTING CHILLER   REPLACEMENT CHILLER

	Existing	Replacement
Chiller Capacity	100 tons	100 tons
Power Consumpton	0.83 kW/ton	0.65 kW/ton
Run Time	2280 hrs/year	2280 hrs/year

Figure 4.2 Chiller Equivalent Annual Cost Comparison, 100 Ton Chiller Capacity
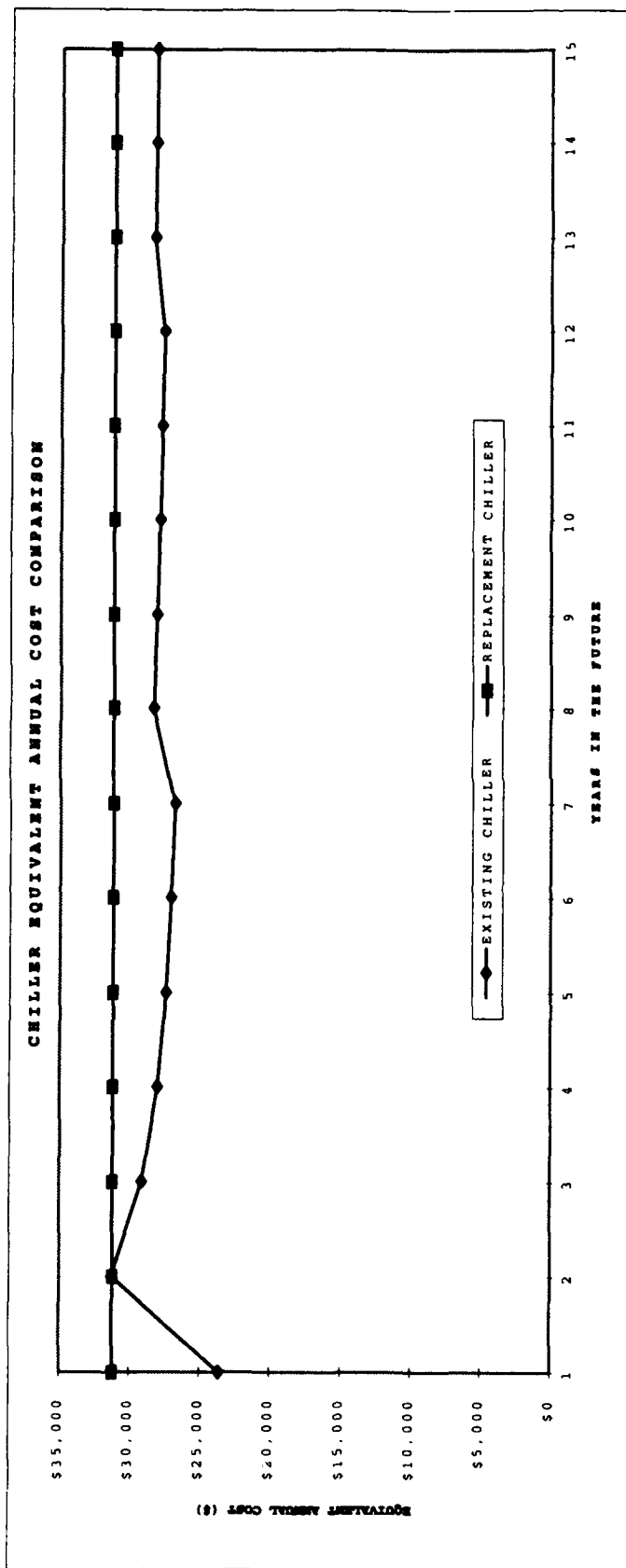
74

Figure 4.3 Chiller Equivalent Annual Cost Comparison, 500 Ton Chiller Capacity
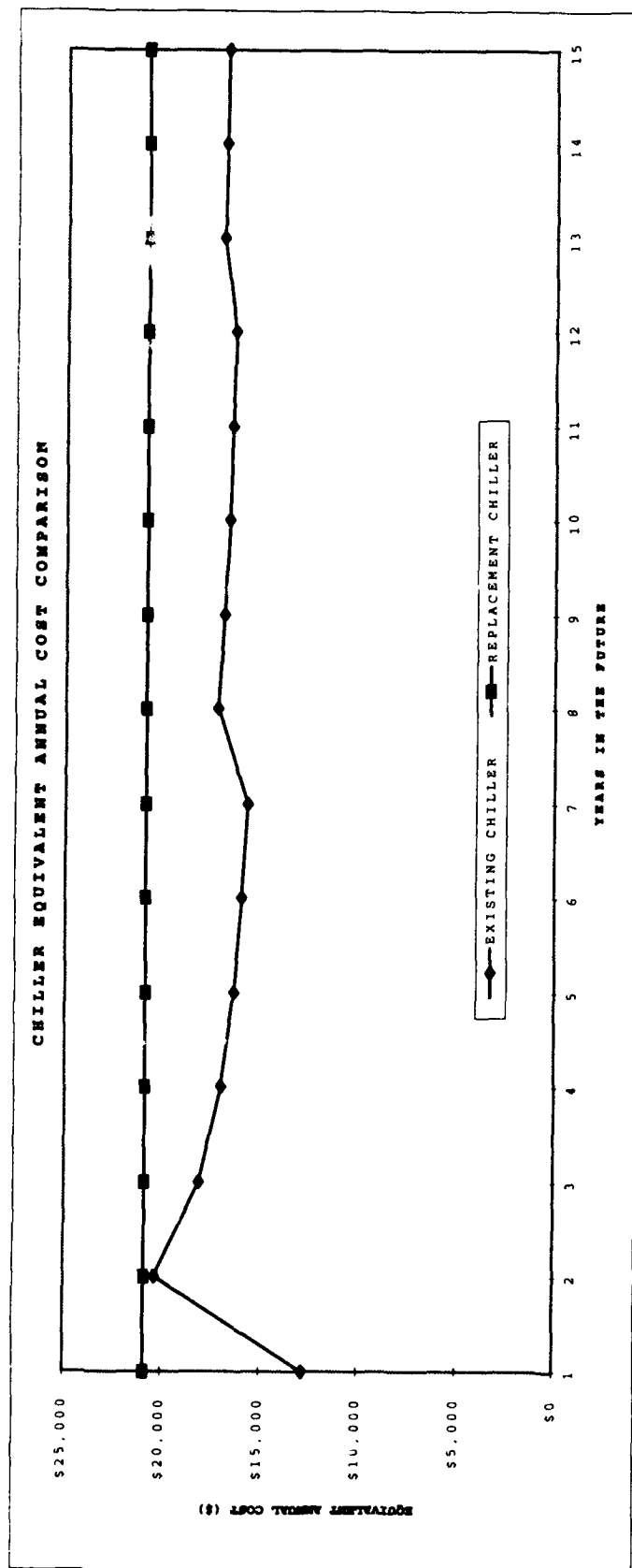
75

Figure 4.4 Chiller Equivalent Annual Cost Comparison, 0.65 kW per Ton

Existing		Replacement	
Chiller Capacity	300 tons		300 tons
Power Consumpton	0.65 kW/ton		0.65 kW/ton
Run Time	2280 hrs/year		2280 hrs/year

76

CHILLER EQUIVALENT ANNUAL COST COMPARISON

EQUIVALENT ANNUAL COST ($)

$25.000
$20.000
$15.000
$10.000
$5.000
$0

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

YEARS IN THE FUTURE

—♦— EXISTING CHILLER   —■— REPLACEMENT CHILLER

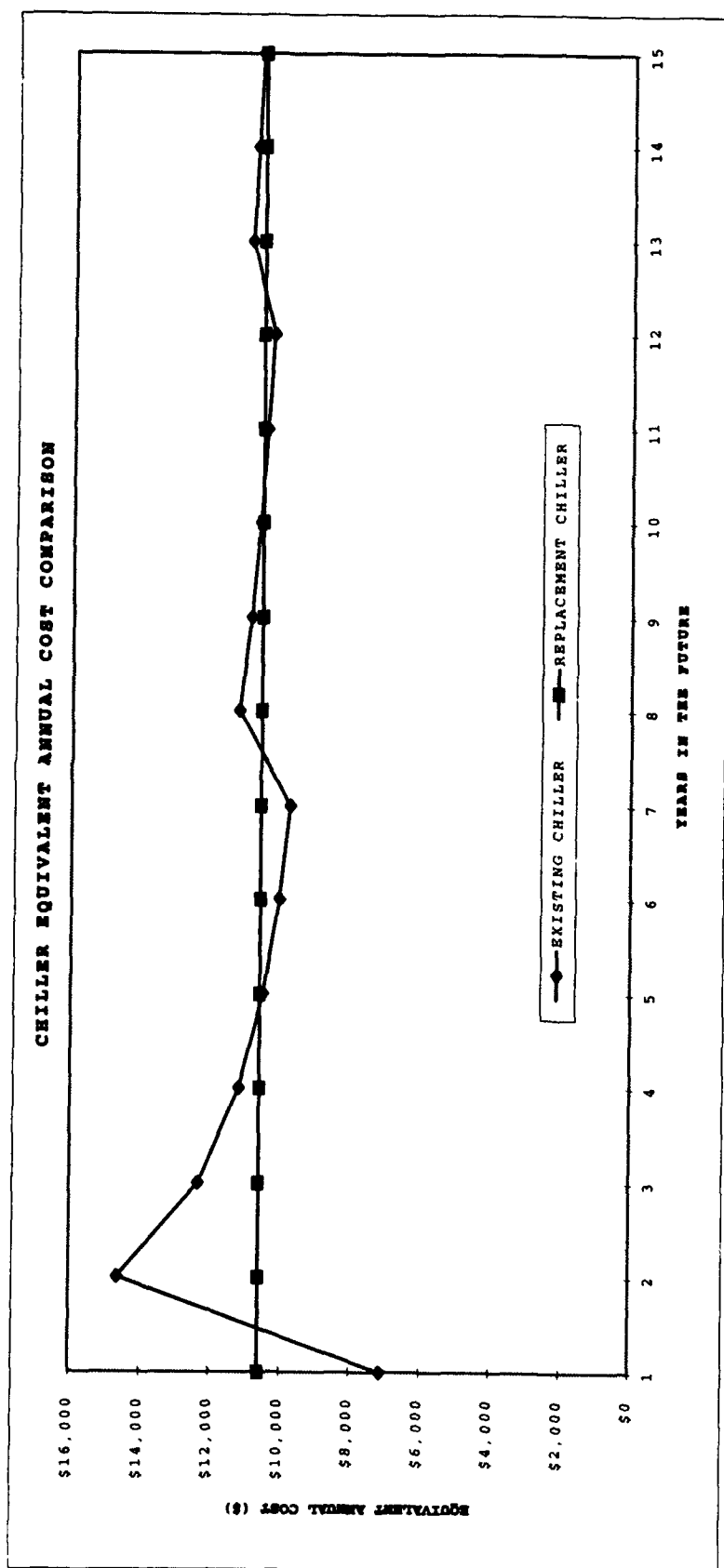|	Existing	Replacement
Chiller Capacity	300 tons	300 tons
Power Consumption	0.9 kw/ton	0.65 kw/ton
Run Time	2280 hrs/year	2280 hrs/year
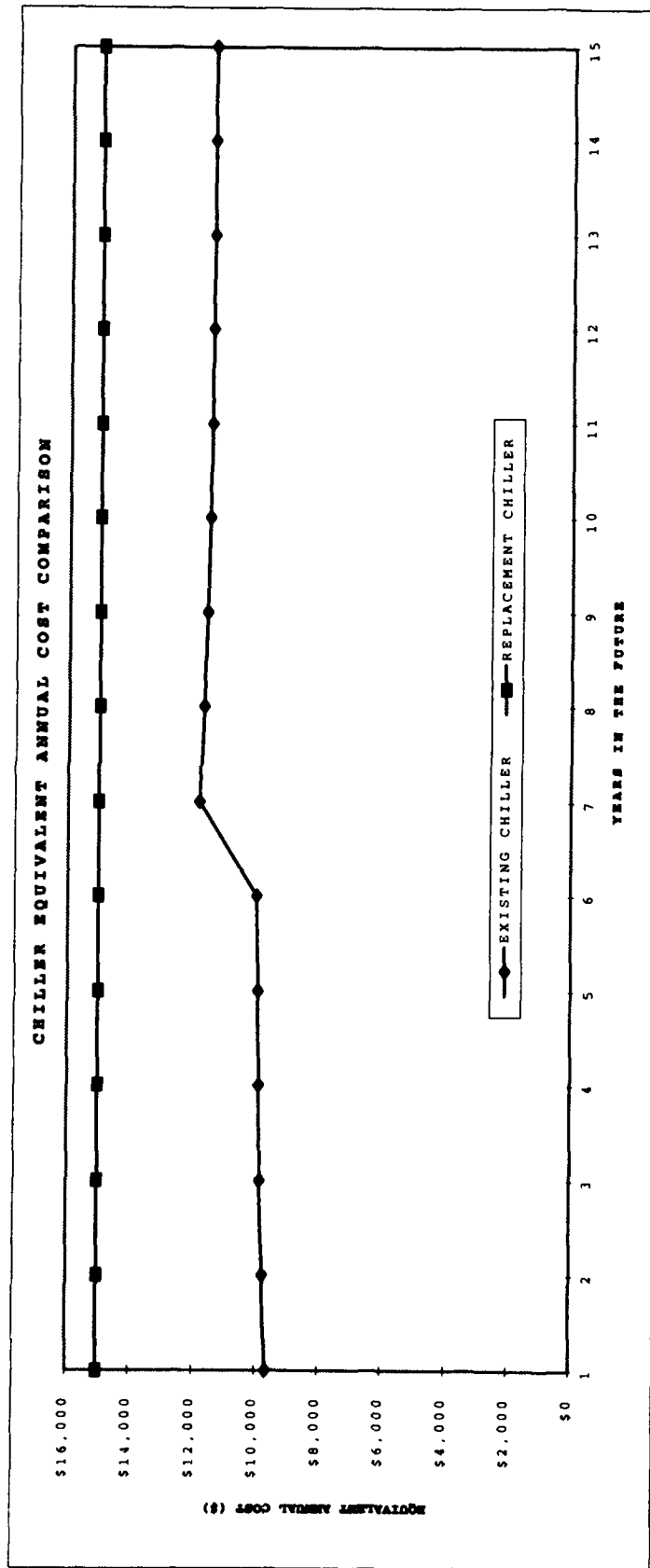
Figure 4.5 Chiller Equivalent Annual Cost Comparison, 0.90 kW per Ton

77

Figure 4.6 Chiller Equivalent Annual Cost Comparison, 1,188 Hours per Year

78
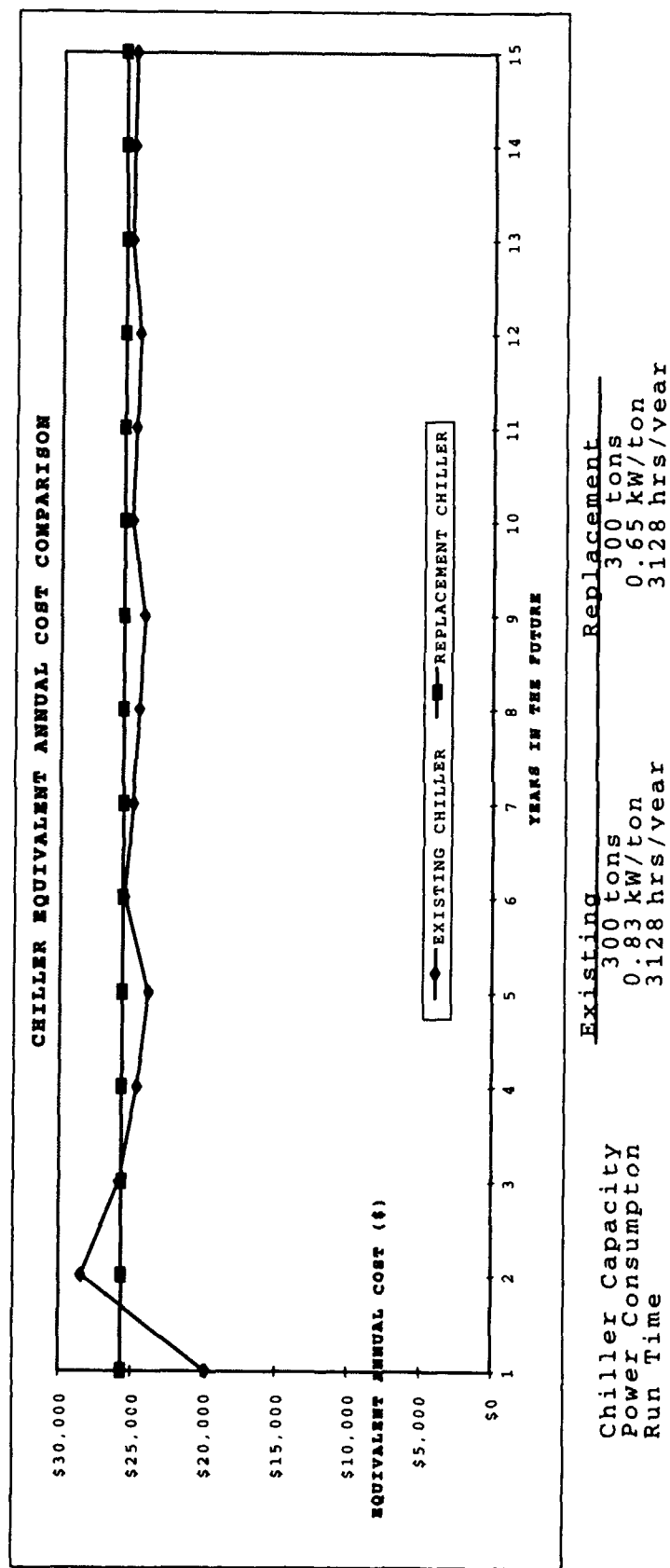
Figure 4.7 Chiller Equivalent Annual Cost Comparison, 3,128 Hours per Year

79

For the 0.90 kW/ton chiller, after the first year, the equivalent annual cost to operate the existing chiller exceeds that of the replacement unit, moving below it in year four.

The cost of electricity is again shown in Figures 4.1, 4.6 and 4.7. Here, run times are compared. In Figure 4.6, where the overall power consumption is greatly reduced, the curve for the existing unit is always below that of the replacement unit. This is not the case where power consumption is increased to 3,128 hrs/year. Here the curve for the existing unit appears more similar to that in Figure 4.1 witn the exception that it has moved closer to the curve for the replacement chiller. It appears then that for those with shorter cooling seasons or who use a chiller to meet peak cooling loads, replacement is never indicated. For applications where run time is longer, the opposite begins to become true.

Another factor that may vary is the price of refrigerant. Using a 300 ton chiller, consuming 0.83 kW/ton and operating 2,280 hours per year as a base, the impact of changes in the cost of refrigerant was investigated. The price of CFC refrigerant for the calculations was increased (decreased) by 20% and 50%. Figure 4.8 shows the results of the sensitivity analysis. The points plotted are shown in Table 4.2. Figure 4.8 shows that with a 20% change in refrigerant price, the equivalent annual cost of the chiller operated for 15 additional years changes by about 1%. At a 50% change in refrigerant price, the equivalent annual cost changes by about 3%. If the cost of refrigerant is removed entirely, the annual savings is about $1,200 or 7% of the total cost. This means that even with increasing cost
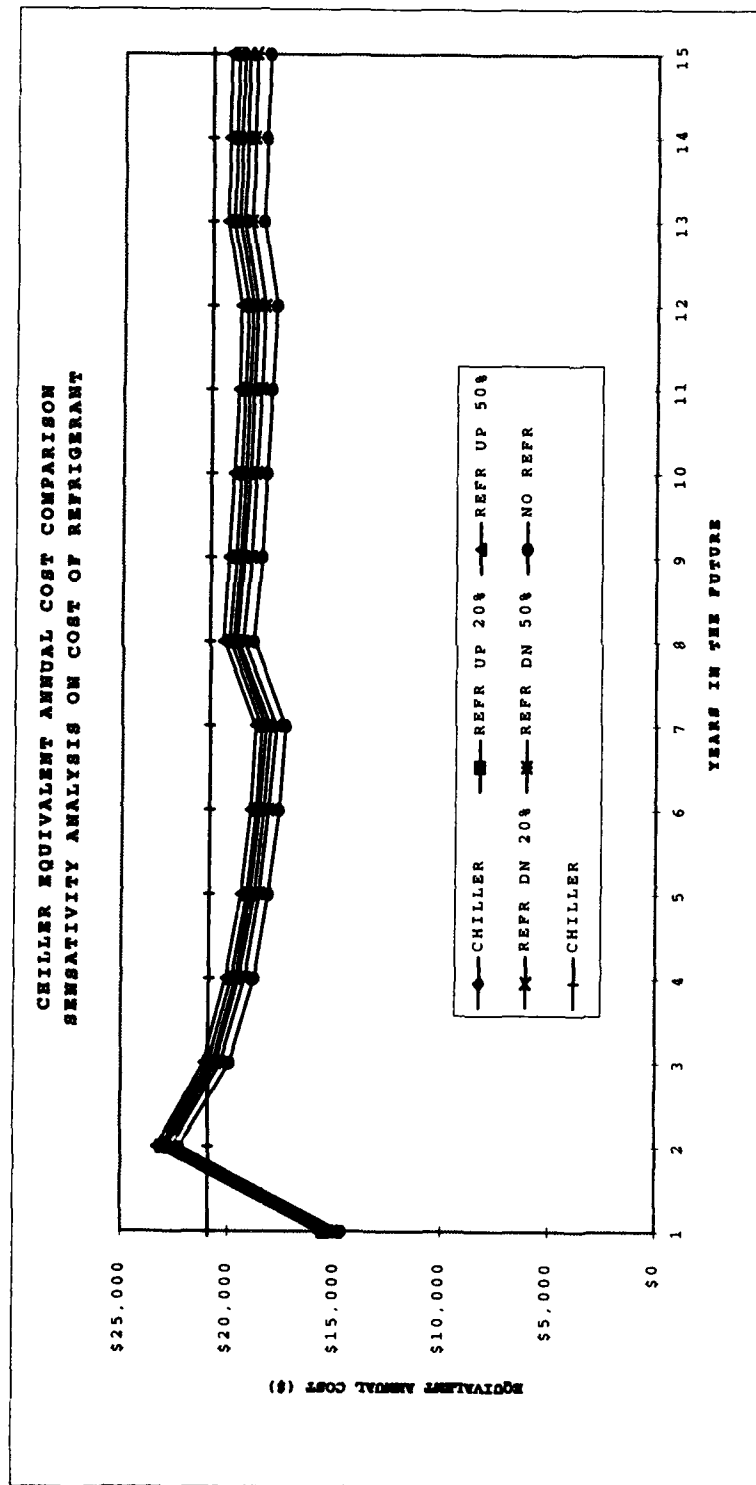
Figure 4.8 Refrigerant Equivalent Annual Cost Sensitivity Analysis

Table 4.2 Data for Refrigerant Equivalent Annual Cost Sensitivity Analysis

Chiller Capacity	300 tons
Power Requirement	0.83 Kw/ton	0.65 Kw/ton
Run Time	2280 hrs/year	2280 hrs/year	2280 hrs/year

| | EXISITING | | | | | | | REPLACEMENT |
YEAR	CHILLER	REFR UP 20%	REFR UP 50%	REFR DN 20%	REFR DN 50%	NO REFR	CHILLER
1	$15,389	$15,529	$15,740	$15,249	$15,038	$14,688	$20,892
2	$22,961	$23,109	$23,331	$22,814	$22,592	$22,222	$20,892
3	$20,720	$20,875	$21,108	$20,565	$20,332	$19,944	$20,892
4	$19,611	$19,855	$20,120	$19,501	$19,236	$18,795	$20,892
5	$18,980	$19,151	$19,407	$18,809	$18,553	$18,126	$20,892
6	$18,566	$18,745	$19,012	$18,388	$18,120	$17,674	$20,892
7	$18,291	$18,477	$18,756	$18,105	$17,826	$17,362	$20,892
8	$19,805	$19,998	$20,288	$19,612	$19,322	$18,839	$20,892
9	$19,521	$19,721	$20,022	$19,320	$19,020	$18,519	$20,892
10	$19,302	$19,509	$19,820	$19,095	$18,784	$18,266	$20,892
11	$19,133	$19,347	$19,668	$18,919	$18,598	$18,063	$20,892
12	$18,999	$19,219	$19,550	$18,778	$18,447	$17,895	$20,892
13	$19,657	$19,884	$20,224	$19,430	$19,089	$18,522	$20,892
14	$19,537	$19,770	$20,120	$19,304	$18,954	$18,371	$20,892
15	$19,439	$19,679	$20,037	$19,200	$18,841	$18,243	$20,892

82

as CFC's become more difficult to obtain, economically, they play a minor part in the operation of a chiller. If there is any reason to replace a chiller it is due to the consumption of electricity.

The service life for the existing and replacement chillers in the calculations above was 30 years. Should the service life of the replacement chiller drop to 20 years, the equivalent annual cost if replacement takes place increases by about $200. This is a reduction of about 1%.

Conclusion

The model has demonstrated that as run time per year or as power consumption per ton of refrigeration effect increases, the chiller should be replaced earlier. It has shown however unless current power consumption is at or near that of the replacement chiller or if run time is short, there is essentially no difference in equivalent annual cost of the existing unit or a replacement. It has further shown, that from an economic point of view, the overall cost of CFC's is not a driving force behind the replacement of chillers.

Chapter Five - Model Implications and Conclusion

This chapter will take a brief look at the issue of CFC replacement as well as the use and applications of the model to determine when equipment replacement should take place. This will include a review of major assumptions made in the model as well as some of the weaknesses found. Next, limitations to the research will be discussed. Finally, the chapter will suggest areas for further investigation.

Model Implications

Originally , the concern was that the cost of operation of chillers was increasing as a result of the increase in the cost of CFC's. Some of these increased costs are generated through taxes placed on CFC's to discourage their use, encouraging the move to alternate refrigerants. However, given the results seen in Chapter 4, the cost of refrigerant is a small factor for an existing machine when compared to electrical and maintenance costs. Rather, if any replacement is made, it should be done to reduce the energy required to provide the required cooling.

The continued low cost of CFC's compared to the chiller as a whole may help to explain why the EPA estimates that only about 16% of the chiller population will be replaced by 1996. Another factor may be the conduct of chiller equipment manufacturers. A Wall Street Journal article estimated the market for chillers at $8 billion. Given these stakes, it pointed out that Trane and Carrier are going head to head over which replacement refrigerant is superior. Trane is putting its hopes behind HCFC-123 while Carrier believes

that HFC-134a will the refrigerant of the future. In each case, they are highly critical of the refrigerant selected by their competitor. As a result, the article states that many engineers and building managers are taking a wait and see attitude. The article, published in May of 1993, pointed out that up until that date only two variances had been issued by the city of Chicago for replacement or conversion of its 1,500 chillers to an alternate refrigerant (McMurray, 10 May 1993:sec. B:1).

Even with the slow transition from CFC's to alternate refrigerants, through use of the model it is possible for organizations to see the costs of continuing to operate existing equipment. By adding information on replacement chillers, the model can provide the point in time when a replacement should occur. Doing this however requires that a number of major assumptions be made which may not apply in a specific case. The most important of these related to placing a value on the existing chiller. The scrap market, used here, may not be the route that is chosen to dispose of a particular chiller. In addition, depending on the installation configuration and transportation requirements, by the time the chiller is delivered to a scrap dealer the value of the transaction to the party using the model may be less than zero.

Another assumption made was that there was no additional cost due to a chiller breakdown. Among others, the breakdown may come in the form of a refrigerant leak, catastrophic failure of the chiller vessel, or breakdown and damage to the motor and compressor. The user must consider his application to determine if he can survive being without air conditioning. Should a chiller failure occur and part or all of the refrigerant be lost, a source of refrigerant will be required. If the chiller is used to provide personal comfort, there may be sufficient time to find refrigerant at the market price with few other

costs incurred. Otherwise, it may become necessary to find the refrigerant and worry about the price later. For a large office building, the cost of a breakdown may include such things as lost time to building tenants because computer systems cannot be operated without a way to remove heat from the building. Repair costs above the annual maintenance costs may also be incurred in bringing the chiller back to operation. If possible, all of these costs should be incorporated into the model.

Finally, the replacement analysis method selected assumes that at the end of the service life, the existing chiller will be replaced. This may not be the case. A given chiller may continue to meet the needs of the user even after passing the end of its service life.

In addition to the assumptions made, there are a number of uncertainties in the calculation. The major one is the cost of the replacement chiller and the cost and frequency of non-annual maintenance. When applying the model, the uncertainty in the cost of the chiller can be reduced by a market survey for the exact size chiller being replaced. In addition the uncertainty surrounding the cost and frequency of maintenance can be reduced through consulting company policy, records of past maintenance, or contracts for future maintenance. While there is some uncertainty about the cost of refrigerant, it has been shown to play a minor role in establishing the cost to operate the current as well as replacement chillers.

Research Limitations

The calculations show, that in many cases, operation of the existing chiller using a CFC refrigerant is more financially advantageous than replacing the chiller with one using an alternate refrigerant. This cannot occur in practice. With production of CFC's being

phased out by 1 January 1996, it is unreasonable to believe that CFC's will still be available in sufficient quantities to meet future air conditioning needs in 2009. Simply running the model and taking action several years in the future is not feasible. Because of the volitile refrigerant market, extending to the scheduled phase out of HCFC's in future decades, the model should be used as a short term tool.

Further, while the model can be used to determine when to make a chiller replacement from a financial point of view, it does not consider qualitative factors such as community relations or company policy. Just what is the value or detriment of the label now required by federal law that a must be placed on products declaring that it contains or has been manufactured with a substance that harms the public health and the environment (United States Congress, 1990:104 Stat.2665)? What would the value be of flying a flag declaring that your plant uses no CFC products? Perhaps in both cases quite substantial.

Areas for Future Research

While the model can be applied to most refrigeration applications, it has been tailored for that of centrifugal chillers. Possible areas for future research include modifying it for other types of mechanical vapor compression equipment. It may be possible to look at the replacement of a centrifugal chiller with a new chiller utilizing a screw compressor.

Future research might also attempt to model the used chiller and retrofit chiller market so that that may be used in establishing a value for the existing chiller. It could also be used in determining if the existing chiller should be retrofitted to use an alternate refrigerant rather than completely replaced.

87

Appendix A - ASHRAE Standard 34

ANSI/ASHRAE 34-1992

ASHRAE®
STANDARD

AN AMERICAN NATIONAL STANDARD

Number Designation and Safety Classification of Refrigerants

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.

1791 Tullie Circle, NE • Atlanta, GA 30329

SPECIAL NOTE

This National Voluntary Consensus Standard was developed under the auspices of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Consensus is defined as "substantial agreement reached by concerned interests according to the judgment of a duly appointed authority, after a concerted attempt at resolving objections. Consensus implies much more than the concept of a simple majority but not necessarily unanimity." This definition is according to the American National Standards Institute (ANSI) of which ASHRAE is a member.

ASHRAE obtains consensus through participation of its national and international members, associated societies, and public review.

ASHRAE Standards are prepared by a Project Committee appointed specifically for the purpose of writing the Standard. The Project Committee Chairman and Vice-Chairman must be members of ASHRAE; while other committee members may or may not be ASHRAE members, all must be technically qualified in the subject area of the Standard. Every effort is made to balance the concerned interests on all Project Committees.

The Manager of Standards of ASHRAE should be contacted for:
    a. interpretation of the contents of this Standard,
    b. participation in the next review of the Standard,
    c. offering constructive criticism for improving the Standard,
    d. permission to reprint portions of the Standard.

CONTENTS

FOREWORD

This standard describes a shorthand way of naming refrigerants and classifies them according to potential hazards. It best fits the category of a Standard Practice. The standard is a revision of ANSI/ASHRAE Standard 34-1989. The principal changes are in the definitions; the addition of uniform, optional, composition-designating prefixes; the adoption of a new safety classification scheme; and the reclassification of the refrigerants with known toxicology and flammability according to the new scheme.

The need to revise Standard 34, almost immediately upon publication of the 1989 version, resulted from growing use of composition-designating prefixes to differentiate between ozone-depleting and chlorine-free compounds. Repeated requests were made to adopt a uniform system in response to the emergence of divergent schemes.[1,2]

A second driving issue was to describe the safety characteristics of commercially available substitutes for chlorofluorocarbon refrigerants. It became apparent that the existing classification scheme, which had evolved over many years, would not be adequate to classify the new and additional refrigerants under consideration. A less arbitrary scheme was devised, and the manner of identification was changed to a consistent toxicity classification letter followed by a flammability index. The previous system had, by contrast, attempted to classify these two independent parameters with a single (or modified single) basic designator. Reversal of the familiar number-letter format of the classification designator was consciously chosen to avoid confusion between the old and revamped safety classifications.

In the case of zeotropes, two groups are now assigned to classify the refrigerants as formulated and for the worst case of fractionation. This dual classification respects the safety grouping needs depending on purpose (e.g., for original transportation requirements and subsequent use).

An additional revision surfaced with regard to the classification of isomers as it became apparent that both the former and several proposed schemes did not result in unique designations. This issue is now resolved for the compounds of practical concern.

Finally, efforts were made to refine the definitions for refrigerant designations and classifications. The need for these changes resulted from increasing focus on refrigerant characteristics not previously of widespread concern and from growing international cooperation in the classification system. The emergence of new refrigerants will require frequent updating to address additional refrigerants in response to environmental needs.

The new safety classification scheme anticipates additional substitute refrigerants beyond those already under consideration based on environmental concerns. The revisions were coordinated with members of a project committee revising ANSI/ASHRAE Standard 15-1989, Safety Code for Mechanical Refrigeration and numerous parties involved in both toxicity and flammability testing.

The definitions incorporated for Threshold Limit Values (TLVs) and Threshold Limit Value–Time-Weighted Average (TLV-TWA) are those developed by the American Conference of Governmental Industrial Hygienists (ACGIH).

Chairman Sundaresan would like to recognize the contributions of the subcommittee chairmen: Jim Calm, Nomenclature and Designations; Ian Shankland, Toxicity; and Curt Lawson, Flammability. Committee members serving as secretary throughout the development of the standard include Floyd Hayes, Jim Lavelle, and Bill Walter. The SPC 34-1989R members would also like to recognize the service of Floyd Hayes and Sydney Miner, who were both active committee members until their deaths in 1991. Proposals made by Floyd were instrumental to the adoption of the improved classification scheme implemented in this standard. Syd provided a wealth of constructive guidance on considerations in classifying refrigerants and the needs of users of this standard. Without the leadership of these individuals, the prompt response of this committee to the needs of users of Standard 34 would not have been possible.

1. PURPOSE

This standard is intended to establish a simple means of referring to common refrigerants instead of using the chemical name, formula, or trade name. It also establishes a uniform system for assigning reference numbers and safety classifications to refrigerants.

2. SCOPE

This standard provides an unambiguous system for numbering refrigerants and assigning composition-designating prefixes for refrigerants. Safety classifications based on toxicity and flammability data are included.

3. DEFINITIONS OF TERMS

azeotropic: blends comprising multiple components of different volatilities that, when used in refrigeration cycles, do not change volumetric composition or saturation temperature as they evaporate (boil) or condense at constant pressure (please compare with definition of *zeotropic* [see below]).

blends: refrigerants consisting of mixtures of two or more different chemical compounds, often used individually as refrigerants for other applications.

compounds: substances formed by the chemical combination of two or more elements in definite proportions by mass.

cyclic compound: an organic compound that contains three or more atoms arranged in a ring structure.

fractionation: a change in composition of a blend by preferential evaporation of the more volatile component(s) or condensation of the less volatile component(s).

glide: the absolute value of the difference between the

starting and ending temperatures of a phase-change process by a refrigerant within a component of a refrigerating system, exclusive of any subcooling or superheating. This term usually describes condensation or evaporation of a zeotrope.

halocarbon (as used in this standard): a hydrocarbon derivative containing one or more of the halogens bromine, chlorine, or fluorine; hydrogen also may be present.

hydrocarbon: a compound containing only the elements hydrogen and carbon.

isomer: one of a group of compounds having the same chemical composition with differing molecular structures. Examples include R-123 and R-123a, both of which contain two carbon, one hydrogen, three fluorine, and two chlorine atoms; both chlorine atoms are bonded to the same carbon atom in R-123 ($CHCl_2CF_3$), but one is bonded to each in R-123a ($CHClFCClF_2$). The methane series of refrigerants cannot form isomers because the single-carbon nucleus does not enable structural variations.

lower flammability limit (LFL): the minimum concentration of the refrigerant that is capable of propagating a flame through a homogeneous mixture of the refrigerant and air under test conditions specified in Reference 3. The LFL normally is expressed as refrigerant percentage by volume. At 25°C (77°F) and 101 kPa (14.7 psia), multiply the volume percent by (0.0004141) · (molecular mass) to obtain kg/m^3 or by (0.0000257) · (molecular mass) to obtain lb/ft^3.[3]

near azeotropic: a zeotropic blend with a temperature glide sufficiently small that it may be disregarded without consequential error in analysis for a specific application.

nonazeotropic: a synonym for zeotropic (defined below), the latter being the preferred though less commonly used descriptor. Both "non" and "a" are negation prefixes, the latter from Latin, and therefore cancel one another (i.e., not-not-zeotropic, hence zeotropic). The double negative results from antecedent interest in, and the need to make a distinction with, azeotropic mixtures.

refrigerant: the fluid used for heat transfer in a refrigerating system; the refrigerant absorbs heat and transfers it at a higher temperature and a higher pressure, usually with a phase change.

relative molecular mass: the ratio of the mass of a molecule to 1/12 of that of carbon-12. The relative molecular mass is numerically equivalent to the molecular weight expressed in g/mol, but it is dimensionless.

saturated: an organic (carbon-containing) compound in which each carbon atom is joined to four other atoms; all of the chemical bonds in a saturated compound are single.

temperature glide: see *glide*.

threshold limit values (TLVs): refer to airborne concentrations of substances and represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects. Because of wide variation in individual susceptibility, however, a small percentage of workers may experience discomfort from some substances at concentrations at or below the threshold limit; a smaller percentage may be affected more seriously by aggravation of a pre-existing

*This definition reprinted by permission of ACGIH.

condition or by development of an occupational illness. Smoking of tobacco is harmful for several reasons. Smoking may act to enhance the biological effects of chemicals encountered in the workplace and may reduce the body's defense mechanisms against toxic substances.

Individuals may also be hypersusceptible or otherwise unusually responsive to some industrial chemicals because of genetic factors, age, personal habits (smoking, alcohol, or other drugs), medication, or previous exposure. Such workers may not be adequately protected from adverse health effects from certain chemicals at concentrations at or below the threshold limits. An occupational physician should evaluate the extent to which such workers require additional protection.

TLVs are based on the best available information from industrial experience, from experimental human and animal studies, and, when possible, from a combination of the three. The basis on which the values are established may differ from substance to substance; protection against impairment of health may be a guiding factor for some, whereas reasonable freedom from irritation, narcosis, nuisance, or other forms of stress may form the basis for others.[4]

threshold limit value–time-weighted average (TLV-TWA): the time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.[4]

toxicity: the ability of a refrigerant to be harmful or lethal due to acute or chronic exposure by contact, inhalation, or ingestion. The effects of concern include, but are not limited to, those of carcinogens, poisons, reproductive toxins, irritants, corrosives, sensitizers, hepatoxins, nephrotoxins, neurotoxins, agents that act on the hematopoietic system, and agents that damage the lungs, skin, eyes, or mucous membranes. For this standard, temporary discomfort at a level that is not impairing is excluded.

zeotropic: blends comprising multiple components of different volatilities that, when used in refrigeration cycles, change volumetric composition and saturation temperatures as they evaporate (boil) or condense at constant pressure. The word is derived from the Greek words *zein* (to boil) and *tropos* (to change).

4. NUMBERING OF REFRIGERANTS

An identifying number shall be assigned to each refrigerant.[1]

4.1 The identifying numbers assigned to the hydrocarbons and halocarbons of the methane, ethane, propane, and cyclobutane series are such that the chemical composition of the compounds can be explicitly determined from the refrigerant numbers, and vice versa, without ambiguity. The molecular structure can be similarly determined for the methane, ethane, and most of the propane series.

4.1.1 The first digit on the right is the number of fluorine (F) atoms in the compound.

4.1.2 The second digit from the right is one more than the number of hydrogen (H) atoms in the compound.

*This definition reprinted by permission of ACGIH.

4.1.3 The third digit from the right is one less than the number of carbon (C) atoms in the compound. When this digit is zero, it is omitted from the number.

4.1.4 The fourth digit from the right is equal to the number of unsaturated carbon-carbon bonds in the compound. When this digit is zero, it is omitted from the number.

4.1.5 In those instances where bromine (Br) is present in place of part or all of the chlorine, the same rules apply, except that the uppercase letter *B* after the designation for the parent chlorofluoro compound shows the presence of bromine. The number following the letter *B* shows the number of bromine atoms present.

4.1.6 The number of chlorine (Cl) atoms in the compound is found by subtracting the sum of fluorine (F), bromine (Br), and hydrogen (H) atoms from the total number of atoms that can be connected to the carbon (C) atoms. For saturated refrigerants, this number is $2n + 2$, where n is the number of carbon atoms. The number is $2n$ for mono-unsaturated and cyclic-saturated refrigerants.

4.1.7 For cyclic derivatives, the letter *C* is used before the identifying refrigerant numbers.

4.1.8 In the case of isomers in the ethane series, each has the same number, with the most symmetrical one indicated by the number alone. As the isomers become more and more unsymmetrical, successive lowercase letters (i.e., *a*, *b*, or *c*) are appended. Symmetry is determined by first summing the atomic mass of the halogen and hydrogen atoms attached to each carbon atom. One sum is subtracted from the other; the smaller the absolute value of the difference, the more symmetrical the isomer.

4.1.9 In the case of isomers in the propane series, each has the same number, with the isomers distinguished by two appended lowercase letters. The first appended letter indicates the substitution on the central carbon atom (C2):

-CCl$_2$-	a
-CClF-	b
-CF$_2$-	c
-CClH-	d
-CFH-	e
-CH$_2$-	f

For halogenated derivatives of cyclopropane, the carbon atom with the largest sum of attached atomic masses shall be considered the *central* carbon atom; for these compounds, the first appended letter is omitted. The second appended letter indicates the relative symmetry of the substituents on the end carbon atoms (C1 and C3). Symmetry is determined by first summing the atomic masses of the halogen and hydrogen atoms attached to the C1 and C3 carbon atoms. One sum is subtracted from the other; the smaller the absolute value of this difference, the more symmetrical the isomer. In contrast to the ethane series, however, the most symmetrical isomer has a second appended letter of *a* (as opposed to no appended letter for ethane isomers); increasingly asymmetrical isomers are assigned successive letters. Appended letters are omitted when no isomers are possible, and the number alone represents the molecular structure unequivocally; for

example, $CF_3CF_2CF_3$, is designated R-218, not R-218ca. An example of this system is given in Appendix A.

4.1.10 Bromine-containing, propane-series isomers cannot be uniquely designated by this system.

4.2 Blends are designated by their respective refrigerant numbers and weight proportions. Refrigerants shall be named in order of increasing normal boiling points of the components. For example, a 10/90 weight % mixture of Refrigerants 12 and 22 will be indicated as R-22/12 (90/10) or Refrigerant 22/12 (90/10). A blend of 92% R-502 (the azeotrope of R-22 and R-115) with 8% R-290 (propane) would be indicated as R-290/22/115 (8/45/47).

4.2.1 Zeotropic blends that have been commercialized shall be assigned an identifying number in the 400 series. This number designates which components are in the mixture but not the amount of each. The amount of each component is designated as described in 4.2. For example, the 90/10 weight % mixture of Refrigerants 12 and 114 would be R-400 (90/10).

4.2.2 Azeotropes that have been commercialized shall be serially assigned an identifying number in the 500 series. It is not necessary to cite the percentages parenthetically once a 500-series number is assigned.

4.3 The 600 series has been assigned to miscellaneous organic compounds and the 700 series to inorganic compounds.

4.3.1 Within the organic 600 series, the assignments are serial.

4.3.2 Within the inorganic 700 series, the relative molecular mass of the compounds is added to 700 to arrive at the identifying refrigerant numbers.

4.3.3 When two or more inorganic refrigerants have the same relative molecular masses, uppercase letters (i.e., *A*, *B*, *C*, etc.) are added to distinguish among them.

5. DESIGNATION

5.1 General This section provides guidance on prefixes for refrigerants to improve uniformity in order to promote understanding. Both technical and nontechnical designations are provided, to be selected based on the nature and audience of the use.

5.2 Identification Refrigerants shall be identified in accordance with Section 5.2.1, 5.2.2, or 5.2.3. Section 5.2.1 shall be used in technical publications (for international uniformity and to preserve archival consistency), on equipment nameplates, and in specifications. Section 5.2.2 can be used for single-component halocarbon refrigerants, where distinction between the presence or absence of chlorine or bromine is pertinent. Composition designation may be appropriate for nontechnical, public, and regulatory communications addressing ozone-depleting compounds. Section 5.2.3 can be used, under the same circumstances as Section 5.2.2, for blends (both azeotropic and zeotropic). Section 5.2.1 shall be used for miscellaneous organic and inorganic compounds.

5.2.1 Technical Prefixes The identifying number, as determined by Section 4, shall be preceded by the letter *R*, the word *Refrigerant* (*Refrigerants* if more than one), or the

manufacturer's trademark or trade name. Examples include: R 12, R-12, Refrigerant 12, <Trade Name> 12, <Trade Name> R 12, R-500, R-22/152a/114 (36/24/40), and R-717. Trademarks and trade names shall not be used to identify refrigerants on equipment nameplates or in specifications.

5.2.2 Composition-Designating Prefixes The identifying number, as determined by Section 4, shall be prefixed by the letter C, for carbon, preceded by B, C, or F—or a combination thereof in this sequence—to signify the presence of bromine, chlorine, or fluorine. Compounds that also contain hydrogen shall be further preceded by the letter H to signify the increased deterioration potential before reaching the stratosphere.[2] Examples include: CFC-11, CFC-12, BCFC-12B1, BFC-13B1, HCFC-22, HC-50, CFC-113, CFC-114, CFC-115, HCFC-123, HCFC-124, HFC-125, HFC-134a, HCFC-141b, HCFC-142b, HFC-143a, HFC-152a, HC-170, and FC-C318.

5.2.3 Recognized blends (whether azeotropic, near-azeotropic, or zeotropic) with assigned numbers can be identified by linking the appropriate composition-designating prefixes of individual components (e.g., CFC/HFC-500). Blends without assigned numbers can be identified using appropriate composition-designating prefixes for each component (e.g., HCFC-22/HFC-152a/CFC-114 [36/24/40]). Linked prefixes (e.g., HCFC/HFC/CFC-22/152a/114 [36/24/40]) and prefixes implying synthesized compositions (e.g., HCFC-500 or HCFC-22/152a/114 [36/24/40]) shall not be used.

5.2.4 Composition-designating prefixes should be used only in nontechnical publications in which the potential for ozone depletion is pertinent. The prefixes specified in Section 5.2.1, augmented if necessary as indicated in Section 5.4, are preferred in other communications. Section 5.2.1 also may be preferable for blends when the number of components makes composition-designating prefixes awkward, such as for those containing more than three individual components (e.g., in tetrary and pentary blends). 5.3 Other prefixes, including *ACFC* and *HFA*, for *alternative to chlorofluorocarbons* and *hydrofluorocarbon alternative*, respectively, shall not be used. Similarly, neither *FC* nor *CFC* shall be used as universal prefixes to signify the fluorocarbon and chlorofluorocarbon families of refrigerants (i.e., other than as stipulated in Section 5.2.2). 5.4 The convention specified in Section 5.2.1 can be complemented with pertinent data, when appropriate, as a preferred alternative to composition-designating prefixes in technical communications. For example, the first mention of R-12 in a discussion of the ozone-depletion issue might read, "R-12, a CFC," or "R-12 (ODP = 1.0)." Similarly, a document on the greenhouse effect could cite "R-22 (GWP = 0.34 relative to R-11)," and one on flammability might refer to "R-152a (LFL = 4.1%)."

6. SAFETY GROUP CLASSIFICATIONS

6.1 Refrigerants shall be classified into safety groups according to the following criteria.

6.1.1 Classification The safety classification shall

consist of two alphanumeric characters (e.g., A2 or B1). The capital letter indicates the toxicity as determined by Section 6.1.2; the arabic numeral denotes the flammability as determined by Section 6.1.3.

6.1.2 Toxicity Classification Refrigerants shall be assigned to one of two classes—A or B—based on allowable exposure:

Class A signifies refrigerants for which toxicity has not been identified at concentrations less than or equal to 400 ppm, based on data used to determine Threshold Limit Value–Time-Weighted Average (TLV–TWA) or consistent indices.

Class B signifies refrigerants for which there is evidence of toxicity at concentrations below 400 ppm, based on data used to determine TLV–TWA or consistent indices.

6.1.3 Flammability Classification Refrigerants shall be assigned to one of three classes—1, 2, or 3—based on flammability. Tests shall be made in accordance with ASTM E681-85 except that the ignition source shall be an electrically activated kitchen match head for halocarbon refrigerants. (Conversion factors to convert LFL from volume % to mass per unit volume, and vice versa, are included in the definition for lower flammability limit (LFL) in Section 3 of the standard.)

Class 1 indicates refrigerants that do not show flame propagation when tested in air at 101 kPa (14.7 psia) and 18°C (65°F).

Class 2 signifies refrigerants having a lower flammability limit (LFL) of more than 0.10 kg/m^3 (0.00625 lb/ft^3) at 21°C and 101 kPa (70°F and 14.7 psia) *and* a heat of combustion of less than 19,000 kJ/kg (8,174 Btu/lb). The heat of combustion shall be calculated assuming that combustion products are in the gas phase and in their most stable state (e.g., C, N, S give CO_2, N_2, SO_3; F and Cl give HF and HCl if there is enough H in the molecule, otherwise they give F_2 and Cl_2; excess H is converted to H_2O).

Class 3 indicates refrigerants that are highly flammable, as defined by an LFL of less than or equal to 0.10 kg/m^3 (0.00625 lb/ft^3) at 21°C and 101 kPa (70°F and 14.7 psia) *or* a heat of combustion greater than or equal to 19,000 kJ/kg (8,174 Btu/lb). The heat of combustion is calculated as explained above in the definition of a Class 2 category.

Definitions of flammability differ depending on the purpose. For example, ammonia is classified for transportation purposes as a nonflammable gas by the U.S. Department of Transportation, but it is a Class 2 refrigerant.

6.1.4 Matrix Diagram of Safety Group Classification System The toxicity and flammability classifications described in Sections 6.1.1, 6.1.2, and 6.1.3 yield six separate safety group classifications (A1, A2, A3, B1, B2, and B3) for refrigerants. These classifications are represent-

ed by the matrix shown in Figure 1. Appendix B is included to provide conversions from the previous safety group classifications (ASHRAE 34-1989) to the current ones.

6.1.5 Safety Classification of Refrigerant Blends Zeotropic blends, whose flammability and/or toxicity characteristics may change as the composition changes during fractionation, shall be assigned a dual safety group classification, with the two classifications separated by a slash (/). Each of the two classifications shall be determined according to the same criteria as a single-component refrigerant (see Sections 6.1.2 and 6.1.3). The first classification listed shall be the classification of the *as formulated* composition of the blend. The second classification listed shall be the classification of the blend composition at *the worst case of fractionation*.

For flammability, "worst case of fractionation" is defined as the composition during fractionation that results in the highest concentration of the flammable component(s) in the vapor or liquid phase. For toxicity, "worst case of fractionation" is defined as the composition during fractionation that results in the highest concentration of the component(s) in the vapor or liquid phase for which the TLV-TWA is less than 400 ppm. The TLV-TWA for a specific blend composition shall be calculated from the TLV-TWA of the individual components (Appendix C of Reference 4).

6.2 Other Standards This classification is to be used in conjunction with other relevant safety standards, such as *ASHRAE Standard 15, Safety Code for Mechanical Refrigeration.*

7. REFRIGERANT CLASSIFICATIONS

Refrigerants are assigned the classifications indicated in Tables 1 and 2.

8. REFERENCES

[1]T. Atwood, "The Need for Standard Nomenclature for Refrigerants," *ASHRAE Journal*, Vol. 31, No. 11, pp. 44-47, November 1989.
[2]J.M. Calm, "Composition Designations for Refrigerants," *ASHRAE Journal*, Vol. 31, No. 11, pp. 48-51, November 1989.
[3]*Concentration Limits of Flammability of Chemicals*, ANSI/ASTM Standard E681-85, American Society of Testing and Materials, Philadelphia, PA, 1984.
[4]*1990-1991 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*, American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 1990.
[5]*ANSI/ASHRAE Standard 15, Safety Code for Mechanical Refrigeration.*

Figure 1 Refrigerant safety group classification.

TABLE 1
Refrigerant Data and Safety Classifications

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	Molecular Mass[a]	Normal Boiling Point[a] (°C)	(°F)	Safety Group
	Methane Series					
10	tetrachloromethane (carbon tetrachloride)	CCl₄	153.8	77	171	B1
11	trichlorofluoromethane	CCl₃F	137.4	24	75	A1
12	dichlorodifluoromethane	CCl₂F₂	120.9	-30	-22	A1
12B1	bromochlorodifluoromethane	CBrClF₂	165.4	-4	25	
12B2	dibromodifluoromethane	CBr₂F₂	209.8	25	77	
13	chlorotrifluoromethane	CClF₃	104.5	-81	-115	A1
13B1	bromotrifluoromethane	CBrF₃	148.9	-58	-72	A1
14	carbon tetrafluoride	CF₄	88.0	-128	-198	A1
20	trichloromethane (chloroform)	CHCl₃	119.4	61	142	
21	dichlorofluoromethane	CHCl₂F	102.9	9	48	B1
22	chlorodifluoromethane	CHClF₂	86.5	-41	-41	A1
22B1	bromodifluoromethane	CHBrF₂	130.9	-15	5	
23	trifluoromethane	CHF₃	70.0	-82	-116	
30	dichloromethane (methylene chloride)	CH₂Cl₂	84.9	40	104	B2
31	chlorofluoromethane	CH₂ClF	68.5	-9	16	
32	difluoromethane (methylene fluoride)	CH₂F₂	52.0	-52	-62	
40	chloromethane (methyl chloride)	CH₃Cl	50.5	-24	-12	B2
41	fluoromethane (methyl fluoride)	CH₃F	34.0	-78	-108	
50	methane	CH₄	16.0	-161	-259	A3
	Ethane Series					
110	hexachloroethane	CCl₃CCl₃	236.8	185	365	
111	pentachlorofluoroethane	CCl₃CCl₂F	220.3	135	275	
112	1,1,2,2-tetrachlorodifluoroethane	CCl₂FCCl₂F	203.8	93	199	
112a	1,1,1,2-tetrachlorodifluoroethane	CCl₃CClF₂	203.8	91	196	
113	1,1,2-trichlorotrifluoroethane	CCl₂FCClF₂	187.4	48	118	A1
113a	1,1,1-trichlorotrifluoroethane	CCl₃CF₃	187.4	46	115	
114	1,2-dichlorotetrafluoroethane	CClF₂CClF₂	170.9	4	38	A1
114a	1,1-dichlorotetrafluoroethane	CCl₂FCF₃	170.9	3	37	
114B2	1,2-dibromotetrafluoroethane	CBrF₂CBrF₂	259.9	47	117	
115	chloropentafluoroethane	CClF₂CF₃	154.5	-39	-38	A1
116	hexafluoroethane	CF₃CF₃	138.0	-79	-110	
120	pentachloroethane	CHCl₂CCl₃	202.3	162	324	
123	2,2-dichloro-1,1,1-trifluoroethane	CHCl₂CF₃	153.0	27	81	B1[d]
123a	1,2-dichloro-1,1,2-trifluoroethane	CHClFCClF₂	153.0	28	82	
124	2-chloro-1,1,1,2-tetrafluoroethane	CHClFCF₃	136.5	-12	10	
124a	1-chloro-1,1,2,2-tetrafluoroethane	CHF₂CClF₂	136.5	-10	14	
125	pentafluoroethane	CHF₂CF₃	120.0	-49	-56	
133a	2-chloro-1,1,1-trifluoroethane	CH₂ClCF₃	118.5	6	43	
134a	1,1,1,2-tetrafluoroethane	CH₂FCF₃	102.0	-26	-15	A1[d]
140a	1,1,1-trichloroethane (methylchloroform)	CH₃CCl₃	133.4	74	165	
141b	1,1-dichloro-1-fluoroethane	CH₃CCl₂F	117.0	32	90	
142b	1-chloro-1,1-difluoroethane	CH₃CClF₂	100.5	-10	14	A2
143a	1,1,1-trifluoroethane	CH₃CF₃	84.0	-47	-53	
150a	1,1-dichloroethane	CH₃CHCl₂	99.0	57	135	
152a	1,1-difluoroethane	CH₃CHF₂	66.0	-25	-13	A2
160	chloroethane (ethyl chloride)	CH₃CH₂Cl	64.5	12	54	
170	ethane	CH₃CH₃	30.0	-89	-128	A3

(continued)

[a] The chemical name, chemical formula, molecular mass, and normal boiling point are not part of this standard.
[b] The preferred chemical name is followed by the popular name in parentheses.
[c] Unclassified refrigerants indicate either insufficient data to classify or no formal request for classification.
[d] Toxicity classification is based on recommended exposure limits provided by chemical suppliers. This rating is provisional and will be reviewed when toxicological testing is completed.
[e] Sublimes.

TABLE 1 (continued)
Refrigerant Data and Safety Classifications

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[c]	Molecular Mass[c]	Normal Boiling Point[c] (°C)	Normal Boiling Point[c] (°F)	Safety Group
	Propane Series					
216ca	1,3-dichloro-1,1,2,2,3,3-hexafluoropropane	$CClF_2CF_2CClF_2$	221.0	36	97	
218	octafluoropropane	$CF_3CF_2CF_3$	188.0	-37	-35	
245cb	1,1,1,2,2-pentafluoropropane	$CF_3CF_2CH_3$	134.0	-18	0	
290	propane	$CH_3CH_2CH_3$	44.0	-42	-44	A3
	Cyclic Organic Compounds					
C316	1,2-dichlorohexafluorocyclobutane	$C_4Cl_2F_6$	233.0	60	100	
C317	chloroheptafluorocyclobutane	C_4ClF_7	216.5	26	79	
C318	octafluorocyclobutane	C_4F_8	200.0	-6	21	A1
	See Table 2 for Blends					
	Miscellaneous Organic Compounds					
	hydrocarbons					
600	butane	$CH_3CH_2CH_2CH_3$	58.1	0	31	A3
600a	2-methyl propane (isobutane)	$CH(CH_3)_3$	58.1	-12	11	A3
	oxygen compounds					
610	ethyl ether	$C_2H_5OC_2H_5$	74.1	35	94	
611	methyl formate	$HCOOCH_3$	60.0	32	89	B2
	sulfur compounds					
620	(Reserved for future assignment)					
	Nitrogen Compounds					
630	methyl amine	CH_3NH_2	31.1	-7	20	
631	ethyl amine	$C_2H_5NH_2$	45.1	17	62	
	Inorganic Compounds					
702	hydrogen	H_2	2.0	-253	-423	A3
704	helium	He	4.0	-269	-452	A1
717	ammonia	NH_3	17.0	-33	-28	B2
718	water	H_2O	18.0	100	212	A1
720	neon	Ne	20.2	-246	-411	A1
728	nitrogen	N_2	28.1	-196	-320	A1
732	oxygen	O_2	32.0	-183	-297	
740	argon	Ar	39.9	-186	-303	A1
744	carbon dioxide	CO_2	44.0	-78[e]	-109[e]	A1
744A	nitrous oxide	N_2O	44.0	-90	-129	
764	sulfur dioxide	SO_2	64.1	-10	14	B1
	Unsaturated Organic Compounds					
1112a	1,1-dichlorodifluoroethene	$CCl_2=CF_2$	133.0	19	66	
1113	chlorotrifluoroethene	$CClF=CF_2$	116.5	-28	-18	
1114	tetrafluoroethene	$CF_2=CF_2$	100.0	-76	-105	
1120	trichloroethene	$CHCl=CCl_2$	131.4	87	189	
1130	1,2-dichloroethene (trans)	$CHCl=CHCl$	96.9	48	118	
1132a	vinylidene fluoride	$CH_2=CF_2$	64.0	-82	-116	
1140	vinyl chloride	$CH_2=CHCl$	62.5	-14	7	B3
1141	vinyl fluoride	$CH_2=CHF$	46.0	-72	-98	
1150	ethene (ethylene)	$CH_2=CH_2$	28.1	-104	-155	A3
1270	propene (propylene)	$CH_3CH=CH_2$	42.1	-48	-54	A3

[a]The chemical name, chemical formula, molecular mass, and normal boiling point are not part of this standard.

[b]The preferred chemical name is followed by the popular name in parentheses.

[c]Unclassified refrigerants indicate either insufficient data to classify or no formal request for classification.

[d]Toxicity classification is based on recommended exposure limits provided by chemical suppliers. This rating is provisional and will be reviewed when toxicological testing is completed.

[e]Sublimes.

TABLE 2
Data and Safety Classifications for Refrigerant Blends

Refrigerant Number	Composition (Weight %)	Azeotropic Temperature (°C)	(°F)	Molecular Mass[a]	Normal Boiling Point[a] (°C)	(°F)	Safety Group
	Zeotropes						
400	R-12/114 (must be specified)	none	none				A1 / A1
	Azeotropes[b]						
500	R-12/152a (73.8/26.2)	0	32	99.3	-33	-27	A1
501	R-22/12 (75.0/25.0) [c]	-41	-42	93.1	-41	-42	A1
502	R-22/115 (48.8/51.2)	19	66	112.0	-45	-49	A1
503	R-23/13 (40.1/59.9)	88	126	87.5	-88	-126	
504	R-32/115 (48.2/51.8)	17	63	79.2	-57	-71	
505	R-12/31 (78.0/22.0) [c]	115	239	103.5	-30	-22	
506	R-31/114 (55.1/44.9)	18	64	93.7	-12	10	

[a]The molecular mass and normal boiling point are not part of this standard.

[b]Azeotropic refrigerants exhibit some segregation of components at conditions of temperature and pressure other than those at which they were formulated. The extent of segregation depends on the particular azeotrope and hardware system configuration.

[c]The exact composition of this azeotrope is in question, and additional experimental studies are needed.

APPENDIX A

Isomer Designation Examples

Table A1 illustrates the designation of isomers for the ethane series with three isomers of dichlorotrifluoroethane:

TABLE A1
Ethane Series Isomers

Isomer	Chemical Formula	W_1	Attached Mass W_2	$|W_1-W_2|$
R-123	$CHCl_2CF_3$	71.9	57.0	14.9
R-123a	$CHClFCClF_2$	55.5	73.4	17.9
R-123b	CCl_2FCHF_2	89.9	39.0	50.9

where

W_i = the sum of the atomic mass of halogens and hydrogens attached to carbon atom i.

Table A2 illustrates the designation of isomers for the propane series with nine isomers of dichloropentafluoropropane:

TABLE A2
Propane Series Isomers

Isomer	Chemical Formula	C2 Group	W_1	Attached Mass W_3	$|W_1-W_3|$
R-225aa	$CF_3CCl_2CHF_2$	CCl_2	57.0	39.0	18.0
R-225ba	$CHClFCClFCF_3$	$CClF$	55.5	57.0	1.5
R-225bb	$CClF_2CClFCHF_2$	$CClF$	73.4	39.0	34.4
R-225ca	$CHCl_2CF_2CF_3$	CF_2	71.9	57.0	14.9
R-225cb	$CHClFCF_2CClF_2$	CF_2	55.5	73.4	17.9
R-225cc	$CCl_2FCF_2CHF_2$	CF_2	89.9	39.0	50.9
R-225da	$CClF_2CHClCF_3$	$CHCl$	73.4	57.0	16.4
R-225ea	$CClF_2CHFCClF_2$	CHF	73.4	73.4	0.0
R-225eb	$CCl_2FCHFCF_3$	CHF	89.9	57.0	32.9

where

C2 = the central (second) carbon atom, and
W_i = the sum of the atomic mass of halogens and hydrogens attached to carbon atom i.

APPENDIX B

Comparison of Previous and Current Safety Classifications

A comparison of the current refrigerant classification system with its predecessor is summarized in Table B1:

TABLE B1
Comparison of Safety Group Classifications to Those under ASHRAE Standard 34-1989

Refrigerant Number	Chemical Formula	Safety Group Old	New
10	CCl_4	2	B1
11	CCl_3F	1	A1
12	CCl_2F_2	1	A1
13	$CClF_3$	1	A1
13B1	$CBrF_3$	1	A1
14	CF_4	1	A1
21	$CHCl_2F$	2	B1
22	$CHClF_2$	1	A1
30	CH_2Cl_2	2	B2
40	CH_3Cl	2	B2
50	CH_4	3a	A3
113	CCl_2FCClF_2	1	A1
114	$CClF_2CClF_2$	1	A1
115	$CClF_2CF_3$	1	A1
123	$CHCl_2CF_3$		B1
134a	CH_2FCF_3		A1
142b	CH_3CClF_2	3b	A2
152a	CH_3CHF_2	3b	A2
170	CH_3CH_3	3a	A3
290	$CH_3CH_2CH_3$	3a	A3
C318	C_4F_8	1	A1
400	R12/114	1	A1/A1
500	R-12/152a	1	A1
501	R-22/12	1	A1
502	R-22/115	1	A1
600	$CH_3CH_2CH_2CH_3$	3a	A3
600a	$CH(CH_3)_3$	3a	A3
611	$HCOOCH_3$	2	B2
702	H_2		A3
704	He		A1
717	NH_3	2	B2
718	H_2O		A1
720	Ne		A1
728	N_2		A1
740	Ar		A1
744	CO_2	1	A1
764	SO_2	2	B1
1140	$CH_2=CHCl$		B3
1150	$CH_2=CH_2$	3a	A3
1270	$CH_3CH=CH_2$	3a	A3

POLICY STATEMENT DEFINING ASHRAE'S CONCERN
FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effects on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the standards and guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive technical committee structure, continue to generate up-to-date standards and guidelines where appropriate and adopt, recommend, and promote those new and revised standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating standards and guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.

ASHRAE®

STANDARD

AN AMERICAN NATIONAL STANDARD

Addendum to

- Used as source
- Needed in Appendix

ırds
of
ınal

©1993   ISSN 1041-2336

AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.

1791 Tullie Circle, NE • Atlanta, GA 30329

SPECIAL NOTE

This National Voluntary Consensus Standard was developed under the auspices of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Consensus is defined as "substantial agreement reached by concerned interests according to the judgment of a duly appointed authority, after a concerted attempt at resolving objections. Consensus implies much more than the concept of a simple majority but not necessarily unanimity." This definition is according to the American National Standards Institute (ANSI) of which ASHRAE is a member.

ASHRAE obtains consensus through participation of its national and international members, associated societies, and public review.

ASHRAE Standards are prepared by a Project Committee appointed specifically for the purpose of writing the Standard. The Project Committee Chairman and Vice-Chairman must be members of ASHRAE; while other committee members may or may not be ASHRAE members, all must be technically qualified in the subject area of the Standard. Every effort is made to balance the concerned interests on all Project Committees.

The Manager of Standards of ASHRAE should be contacted for:
   a. interpretation of the contents of this Standard,
   b. participation in the next review of the Standard,
   c. offering constructive criticism for improving the Standard,
   d. permission to reprint portions of the Standard.

FOREWORD

The purposes of this addendum to ANSI/ASHRAE 34-1992 are to modify Table 1 by adding safety classifications for refrigerants R-124, R-125, and R-218; to modify Table 2 by adding refrigerant number designations and safety classifications for several blends of R-401 and R-402; and to remove the provisional status of the safety classifications for R-123 and R-134a. In addition, some of the chemical names have been changed in order to be consistent with International Union of Pure and Applied Chemistry (IUPAC) nomenclature convention.

ADDENDUM

1. The correction indicated in Errata Sheet No. 1, issued on December 8, 1992, is being included for information.

    6.1.3 Correct the flammability test temperature specified for Class 1, from 18°C (65°F) to 21°C (70°F), so as to be consistent with the 21°C (70°F) flammability test temperatures specified elsewhere in 6.1.3 for Class 2 and Class 3. The corrected text for Class 1 reads as follows:

    Class 1 indicates refrigerants that do not show flame propagation when tested in air at 101 kPa (14.7 psia) and 21°C (70°F)

2. In the following tables, the proposed additions are indicated by shading and deletions by strike-throughs. *Exception*: the asterisk (*) footnote to Table 1 indicates deleting of footnote d from those safety classifications.

TABLE 1
Refrigerant Data and Safety Classifications

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	Molecular Mass[a]	Normal Boiling Point[a] (°C)	Normal Boiling Point[a] (°F)	Safety Group
Methane Series						
10	tetrachloromethane (carbon tetrachloride)	CCl_4	153.8	77	171	B1
11	trichlorofluoromethane	CCl_3F	137.4	24	75	A1
12	dichlorodifluoromethane	CCl_2F_2	120.9	-30	-22	A1
12B1	bromochlorodifluoromethane	$CBrClF_2$	165.4	-4	25	
12B2	dibromodifluoromethane	CBr_2F_2	209.8	25	77	
13	chlorotrifluoromethane	$CClF_3$	104.5	-81	-115	A1
13B1	bromotrifluoromethane	$CBrF_3$	148.9	-58	-72	A1
14	tetrafluoromethane (carbon tetrafluoride)	CF_4	88.0	-128	-198	A1
20	trichloromethane (chloroform)	$CHCl_3$	119.4	61	142	
21	dichlorofluoromethane	$CHCl_2F$	102.9	9	48	B1
22	chlorodifluoromethane	$CHClF_2$	86.5	-41	-41	A1
22B1	bromodifluoromethane	$CHBrF_2$	130.9	-15	5	
23	trifluoromethane	CHF_3	70.0	-82	-116	
30	dichloromethane (methylene chloride)	CH_2Cl_2	84.9	40	104	B2
31	chlorofluoromethane	CH_2ClF	68.5	-9	16	
32	difluoromethane (methylene fluoride)	CH_2F_2	52.0	-52	-62	
40	chloromethane (methyl chloride)	CH_3Cl	50.5	-24	-12	B2
41	fluoromethane (methyl fluoride)	CH_3F	34.0	-78	-108	
50	methane	CH_4	16.0	-161	-259	A3
	Ethane Series					
110	hexachloroethane	CCl_3CCl_3	236.8	185	365	
111	pentachlorofluoroethane	CCl_3CCl_2F	220.3	135	275	
112	1,1,2,2-tetrachloro-1,2-difluoroethane	CCl_2FCCl_2F	203.8	93	199	
112a	1,1,1,2-tetrachloro-2,2-difluoroethane	CCl_3CClF_2	203.8	91	196	
113	1,1,2-trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	187.4	48	118	A1
113a	1,1,1-trichloro-2,2,2-trifluoroethane	CCl_3CF_3	187.4	46	115	
114	1,2-dichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	170.9	4	38	A1
114a	1,1-dichloro-1,2,2,2-tetrafluoroethane	CCl_2FCF_3	170.9	3	37	
114B2	1,2-dibromo-1,1,2,2-tetrafluoroethane	$CBrF_2CBrF_2$	259.9	47	117	
115	chloropentafluoroethane	$CClF_2CF_3$	154.5	-39	-38	A1
116	hexafluoroethane	CF_3CF_3	138.0	-79	-110	
120	pentachloroethane	$CHCl_2CCl_3$	202.3	162	324	
123	2,2-dichloro-1,1,1-trifluoroethane	$CHCl_2CF_3$	153.0	27	81	B1*
123a	1,2-dichloro-1,1,2-trifluoroethane	$CHClFCClF_2$	153.0	28	82	
124	2-chloro-1,1,1,2-tetrafluoroethane	$CHClFCF_3$	136.5	-12	10	A1[d]
124a	1-chloro-1,1,2,2-tetrafluoroethane	$CClF_2CHF_2$	136.5	-10	14	
125	pentafluoroethane	CHF_2CF_3	120.0	-49	-56	A1[d]
133a	2-chloro-1,1,1-trifluoroethane	CH_2ClCF_3	118.5	6	43	
134a	1,1,1,2-tetrafluoroethane	CF_3CH_2F	102.0	-26	-15	A1*
140a	1,1,1-trichloroethane (methyl chloroform)	CCl_3CH_3	133.4	74	165	
141b	1,1-dichloro-1-fluoroethane	CCl_2FCH_3	117.0	32	90	
142b	1-chloro-1,1-difluoroethane	$CClF_2CH_3$	100.5	-10	14	A2
143a	1,1,1-trifluoroethane	CF_3CH_3	84.0	-47	-53	
150a	1,1-dichloroethane	$CHCl_2CH_3$	99.0	57	135	
152a	1,1-difluoroethane	CHF_2CH_3	66.0	-25	-13	A2
160	chloroethane (ethyl chloride)	CH_3CH_2Cl	64.5	12	54	
170	ethane	CH_3CH_3	30.0	-89	-128	A3

(continued)

[a] The chemical name, chemical formula, molecular mass, and normal boiling point are not part of this standard.

[b] The preferred chemical name is followed by the popular name in parentheses.

[c] Unclassified refrigerants indicate either insufficient data to classify or no formal request for classification.

[d] Toxicity classification is based on recommended exposure limits provided by chemical suppliers. This rating is provisional and will be reviewed when toxicological testing is completed.

[e] Sublimes.

* indicates removal of provisional status of the classification.

TABLE 1 (continued)
Refrigerant Data and Safety Classifications

Refrigerant Number	Chemical Name[a,b]	Chemical Formula[a]	Molecular Mass[a]	Normal Boiling Point[a] (°C)	(°F)	Safety Group
	Propane Series					
216ca	1,3-dichloro-1,1,2,2,3,3-hexafluoropropane	$CClF_2CF_2CClF_2$	221.0	36	97	
218	octafluoropropane	$CF_3CF_2CF_3$	188.0	-37	-35	A1
245cb	1,1,1,2,2-pentafluoropropane	$CF_3CF_2CH_3$	134.0	-18	0	
290	propane	$CH_3CH_2CH_3$	44.0	-42	-44	A3
	Cyclic Organic Compounds					
C316	1,2-dichloro-1,2,3,3,4,4-hexafluorocyclobutane	$C_4Cl_2F_6$	233.0	60	100	
C317	chloroheptafluorocyclobutane	C_4ClF_7	216.5	26	79	
C318	octafluorocyclobutane	C_4F_8	200.0	-6	21	A1
	See Table 2 for Blends					
	Miscellaneous Organic Compounds					
	hydrocarbons					
600	butane	$CH_3CH_2CH_2CH_3$	58.1	0	31	A3
600a	2-methyl propane (isobutane)	$CH(CH_3)_3$	58.1	-12	11	A3
	oxygen compounds					
610	ethyl ether	$C_2H_5OC_2H_5$	74.1	35	94	
611	methyl formate	$HCOOCH_3$	60.0	32	89	B2
	sulfur compounds					
620	(Reserved for future assignment)					
	Nitrogen Compounds					
630	methyl amine	CH_3NH_2	31.1	-7	20	
631	ethyl amine	$C_2H_5NH_2$	45.1	17	62	
	Inorganic Compounds					
702	hydrogen	H_2	2.0	-253	-423	A3
704	helium	He	4.0	-269	-452	A1
717	ammonia	NH_3	17.0	-33	-28	B2
718	water	H_2O	18.0	100	212	A1
720	neon	Ne	20.2	-246	-411	A1
728	nitrogen	N_2	28.1	-196	-320	A1
732	oxygen	O_2	32.0	-183	-297	
740	argon	Ar	39.9	-186	-303	A1
744	carbon dioxide	CO_2	44.0	-78[e]	-109[e]	A1
744A	nitrous oxide	N_2O	44.0	-90	-129	
764	sulfur dioxide	SO_2	64.1	-10	14	B1
	Unsaturated Organic Compounds					
1112a	1,1-dichloro-2,2-difluoroethene	$CCl_2 = CF_2$	133.0	19	66	
1113	1-chloro-1,2,2-trifluoroethene	$CClF = CF_2$	116.5	-28	-18	
1114	tetrafluoroethene	$CF_2 = CF_2$	100.0	-76	-105	
1120	trichloroethene	$CHCl = CCl_2$	131.4	87	189	
1130	1,2-dichloroethene (trans)	$CHCl = CHCl$	96.9	48	118	
1132a	1,1-difluoroethene (vinylidene fluoride)	$CF_2 = CH_2$	64.0	-82	-116	
1140	chloroethene (vinyl chloride)	$CHCl = CH_2$	62.5	-14	7	B3
1141	fluoroethene (vinyl fluoride)	$CHF = CH_2$	46.0	-72	-98	
1150	ethene (ethylene)	$CH_2 = CH_2$	28.1	-104	-155	A3
1270	propene (propylene)	$CH_3CH = CH_2$	42.1	-48	-54	A3

[a] The chemical name, chemical formula, molecular mass, and normal boiling point are not part of this standard.

[b] The preferred chemical name is followed by the popular name in parentheses.

[c] Unclassified refrigerants indicate either insufficient data to classify or no formal request for classification.

[d] Toxicity classification is based on recommended exposure limits provided by chemical suppliers. This rating is provisional and will be reviewed when toxicological testing is completed.

[e] Sublimes.

TABLE 2
Data and Safety Classifications for Refrigerant Blends

Refrigerant Number	Composition (Weight %)	Azeotropic Temperature (°C)	(°F)	Molecular Mass[a]	Normal Boiling Point[a] (°C)	(°F)	Safety Group
	Zeotropes						
400	R-12/114 (must be specified)	none	none				A1 / A1
401	R-22/152a/124 (53/13/34)						A1 / A1[d e]
401	R-22/152a/124 (61/11/28)						A1 / A1[d e]
401	R-22/152a/124 (33/15/52)						A1 / A1[d e]
402	R-125/290/22 (60/2/38)						A1 / A1[d f]
402	R-125/290/22 (38/2/60)						A1 / A1[d f]
	Azeotropes[b]						
500	R-12/152a (73.8/26.2)	0	32	99.3	-33	-27	A1
501	R-22/12 (75.0/25.0) [c]	-41	-42	93.1	-41	-42	A1
502	R-22/115 (48.8/51.2)	19	66	112.0	-45	-49	A1
503	R-23/13 (40.1/59.9)	88	126	87.5	-88	-126	
504	R-32/115 (48.2/51.8)	17	63	79.2	-57	-71	
505	R-12/31 (78.0/22.0) [c]	115	239	103.5	-30	-22	
506	R-31/114 (55.1/44.9)	18	64	93.7	-12	10	

[a] The molecular mass and normal boiling point are not part of this standard.

[b] Azeotropic refrigerants exhibit some segregation of components at conditions of temperature and pressure other than those at which they were formulated. The extent of segregation depends on the particular azeotrope and hardware system configuration.

[c] The exact composition of this azeotrope is in question, and additional experimental studies are needed.

[d] Toxicity classification is based on recommended exposure limits provided by chemical suppliers. This rating is provisional and will be reviewed when toxicological testing is completed.

[e] Composition tolerances are (±2/+0.5,-1.5/±1)

[f] Composition tolerances are (±2/±1/±2)

POLICY STATEMENT DEFINING ASHRAE'S CONCERN FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effects on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the standards and guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive technical committee structure, continue to generate up-to-date standards and guidelines where appropriate and adopt, recommend, and promote those new and revised standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating standards and guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.

Appendix B - Derivation Of Equal-Payment-Series And Uniform Gradient-Series Factors

Equal-Payment Series Factors

For a series of equal payments of value A, the future value F, may be calculated using the equation:

$$F = A(1) + A(1 + i)^1 + A(1 + i)^2 + ... + A(1 + i)^{n-2} + A(1 + i)^{n-1}$$

If multiplied by $(1 + i)$, the equation becomes:

$$F(1 + i) = A(1 + i)^1 + A(1 + i)^2 + ... + A(1 + i)^{n-1} + A(1 + i)^n$$

Subtracting the first equation from the second gives

$$F(1 + i) - F = -A + A(1 + i)^n$$

or

$$F = A([(1 + i)^n - 1]/i)$$

The factor $([(1 + i)^n - 1]/i)$ is the equal-payment-series compound-amount factor or (F/A,i,n). The inverse of the factor multiplied by the future value results in the equal-payment-series sinking-fund factor. Combining the relationship between present and future value into the equation will result in the equal-payment-series capital-recovery and equal-payment-series present-worth factors.

Uniform Gradient-Series Factor

A uniform gradient may often be expressed as A_1, $A_1 + G$, $A_1 + 2G$, ..., $A_1 + (n - 1)G$.

Where A_1 is the payment at the end of the first year, G is the annual change or gradient, and n is the number of years. See below.
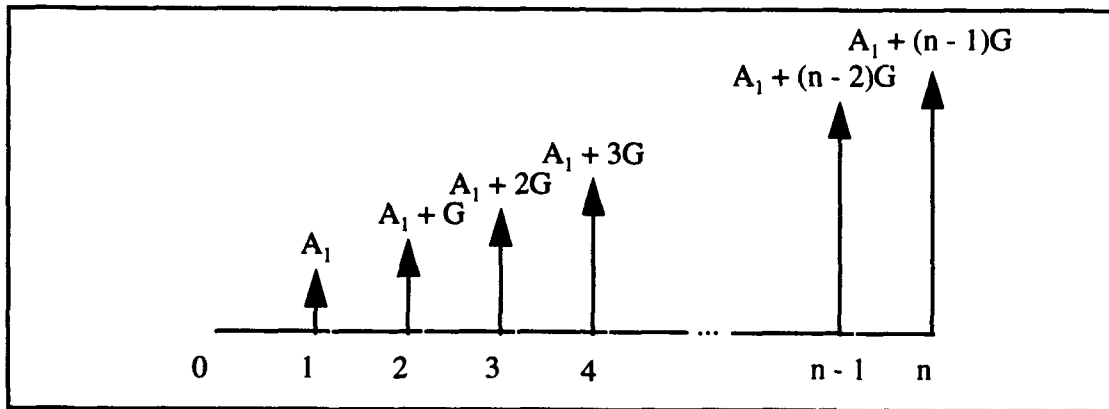
The uniform gradient series can be considered to be made up of a series of equal payments, A_1 and a gradient series 0, G, 2G,... (n-1)G. This can be represented as $A = A_1 + A_2$ where

$$A_2 = G/i - (nG/i)((i/(1 + i)^n - 1)$$

or

$$A_2 = G[1/i - (n/i)(A/F,i,n)]$$

$[1/i - (n/i)(A/F,i,n)]$ is called the gradient factor. The equivalent equal annual payment is

$$A = A_1 + G(A/G,i,n)$$

Fabrycky, Wolter J. and G.J. Thuesen, <u>Economic Decision Analysis</u> (Englewood Cliffs NJ: Prentice-Hall, Inc., 1974), pp. 50-54.

111

Appendix C - Interest Factors and Designations

	Designation	Factor
Single Payment, Compound-Amount Factor	$F = P(F/P,i,n)$	$F = P(1 + i)^n$
Single Payment, Present-Worth Factor	$P = F(P/F,i,n)$	$P = F\left[\dfrac{1}{(1 + i)^n}\right]$
Equal-Payment Series, Compound-Amount Factor	$F = A(F/A,i,n)$	$F = A\left[\dfrac{(1 + i)^n - 1}{i}\right]$
Equal-Payment Series, Sinking Fund Factor	$A = F(A/F,i,n)$	$A = F\left[\dfrac{i}{(1 + i)^n - 1}\right]$
Equal-Payment Series, Present-Worth Factor	$P = A(P/A,i,n)$	$P = A\left[\dfrac{(1 + i)^n - 1}{i(1 + i)^n}\right]$
Equal Payment Series, Capital Recovery Factor	$A = P(A/P,i,n)$	$A = P\left[\dfrac{i(1 + i)^n}{(1 + i)^n - 1}\right]$
Uniform Gradient-Series Factor	$A = G(A/G,i,n)$	$A = G\left[\dfrac{1}{i} - \dfrac{n}{(1 + i)^n - 1}\right]$

Fabrycky, Wolter J. and G.J. Thuesen, <u>Economic Decision Analysis</u> (Englewood Cliffs NJ: Prentice-Hall, Inc., 1974), p. 56.

Appendix D - Salvage Value Calculations

Salvage Value is broken down into two components, the salvage value of the structural portions of the chiller and the salvage value of the refrigerant which the chiller contains. Using information provided by The Trane Co. on their current 200 ton and 400 ton capacity chillers, it is possible to estimate the weight of centrifugal chillers. The value of the structure can be estimated by multiplying the weight by the current price for scrap metal.

<u>Salvage Value of Equipment</u>:

Weight of 400 ton capacity chiller less refrigerant charge:

           Chiller #1:   16,000 lbs
           Chiller #2:   18,200 lbs

Average Weight of Chillers: 17,100 lbs

Weight of 200 ton capacity chiller less refrigerant charge:

           Chiller #1:   11,500 lbs

(Rapier, 1994).

- Assume that the weights of the 400 and 200 ton capacity chillers for which the data was obtained are representative of the weights of all chillers of the same capacity.

- Assume that for the range of capacities concerned, the 100 to 500 ton range, the weight for chillers of other capacities can be determined by linear regression.

113

Therefore:

Capacity of Chiller	Weight of Chiller
100 tons	8700 lbs
200	11500
300	14300
400	17100
500	19900

Chillers are built of steel and copper tubing. Steels of different grades are used in piping, condenser and evaporator walls, compressor impeller and casing, and the motor. The condenser and evaporator contain copper tubing to facilitate heat transfer. A scrap dealer must dismantle a chiller, cleaning parts if required, identifying the type of material (type of steel), and sort it into proper categories.

- Assume that the time required for the dealer to dismantle the chiller, clean, identify, and sort the materials is such that the price offered for the various components would be that of common steel.
- Common scrap steel can currently be sold to a scrap dealer for $0.027/lb (Miller, 1994).

Using the weights calculated above, the salvage value of the structure is:

Capacity of Chiller	Scrap Value
100 tons	$235
200	311
300	386
400	462
500	537

Salvage Value of Refrigerant:

The salvage value of the refrigerant for a chiller is a function of the size of the chiller (quantity of refrigerant), and the year in which the machine is scrapped. As time passes,

the refrigerant will become more valuable as production of new refrigerant stops and an unsatisfied demand continues to be present. At the present time, new CFC-11 sells for about $9.75 per pound. Recycled CFC-11 sells for about $7.00 per pound. Currently, refrigerant can be sold to a recycler for about $3.00 per pound (Elkins, 1994). Based on this, the reclaimer/recycler keeps about 60% of the sale price.

- Assume that the reclaimer/recycler will pay 40% of the sale price of refrigerant for used refrigerant.

- Assume that the price of reclaimed/recycled refrigerant will follow the estimated cost of commercial refrigerant.

- Assume that based on information from Trane and SnyderGeneral, two pounds of refrigerant is required per ton of capacity.

- CFC-11 is predominantly used in commercial and industrial chillers. Salvage value will be based on the cost of that refrigerant. The cost of CFC-12, the other popular refrigerant in use varies from CFC-11 by no more than 10%. See the following tables and charts on cost of refrigerants, salvage value for refrigerants and total salvage value of chillers.

Salvage Value for Refrigerant

Salvage Year	Chiller Capacity (tons)				
	100	200	300	400	500
1994	$779	$1,559	$2,338	$3,118	$3,897
1995	$935	$1,871	$2,806	$3,742	$4,677
1996	$1,039	$2,079	$3,118	$4,157	$5,197
1997	$1,143	$2,286	$3,430	$4,573	$5,716
1998	$1,273	$2,546	$3,819	$5,093	$6,366
1999	$1,377	$2,754	$4,131	$5,508	$6,885
2000	$1,507	$3,014	$4,521	$6,028	$7,535
2001	$1,619	$3,237	$4,856	$6,475	$8,094
2002	$1,739	$3,479	$5,218	$6,957	$8,696
2003	$1,855	$3,710	$5,566	$7,421	$9,276
2004	$1,976	$3,952	$5,928	$7,904	$9,880
2005	$2,092	$4,183	$6,275	$8,366	$10,458
2006	$2,211	$4,422	$6,633	$8,844	$11,055
2007	$2,329	$4,657	$6,986	$9,314	$11,643
2008	$2,447	$4,894	$7,341	$9,788	$12,235
2009	$2,564	$5,129	$7,693	$10,258	$12,822
2010	$2,683	$5,366	$8,049	$10,732	$13,415
2011	$2,801	$5,601	$8,402	$11,203	$14,004
2012	$2,919	$5,838	$8,757	$11,675	$14,594
2013	$3,037	$6,074	$9,110	$12,147	$15,184
2014	$3,155	$6,310	$9,465	$12,620	$15,775
2015	$3,273	$6,546	$9,819	$13,092	$16,364

116

Total Salvage Value for Chiller

Salvage Year	Chiller Capacity (tons)				
	100	200	300	400	500
1994	$1,014	$1,870	$2,724	$3,580	$4,434
1995	$1,170	$2,182	$3,192	$4,204	$5,214
1996	$1,274	$2,390	$3,504	$4,619	$5,734
1997	$1,378	$2,597	$3,816	$5,035	$6,253
1998	$1,508	$2,857	$4,205	$5,555	$6,903
1999	$1,612	$3,065	$4,517	$5,970	$7,422
2000	$1,742	$3,325	$4,907	$6,490	$8,072
2001	$1,854	$3,548	$5,242	$6,937	$8,631
2002	$1,974	$3,790	$5,604	$7,419	$9,233
2003	$2,090	$4,021	$5,952	$7,883	$9,813
2004	$2,211	$4,263	$6,314	$8,366	$10,417
2005	$2,327	$4,494	$6,661	$8,828	$10,995
2006	$2,446	$4,733	$7,019	$9,306	$11,592
2007	$2,564	$4,968	$7,372	$9,776	$12,180
2008	$2,682	$5,205	$7,727	$10,250	$12,772
2009	$2,799	$5,440	$8,079	$10,720	$13,359
2010	$2,918	$5,677	$8,435	$11,194	$13,952
2011	$3,036	$5,912	$8,788	$11,665	$14,541
2012	$3,154	$6,149	$9,143	$12,137	$15,131
2013	$3,272	$6,385	$9,496	$12,609	$15,721
2014	$3,390	$6,621	$9,851	$13,082	$16,312
2015	$3,508	$6,857	$10,205	$13,554	$16,901

Salvage Value for HCFC-123

Salvage Value for Refrigerant

Salvage	Chiller Capacity (tons)				
Year	100	200	300	400	500
2024	$395	$790	$1,185	$1,580	$1,975

Total Salvage Value for Chiller

Salvage	Chiller Capacity (tons)				
Year	100	200	300	400	500
2024	$630	$1,101	$1,571	$2,042	$2,512

Cost of Refrigerrant in Commercial Quantities
in 1994 $ per pound

Year	CFC-11	CFC-12	HCF-134a	HCFC-123	HCFC-22
1990	$6.17	$5.96	$16.70	$7.76	$1.90
1991	$6.17	$6.23	$13.07	$6.60	$1.90
1992	$7.15	$7.04	$10.46	$6.02	$1.90
1993	$9.42	$9.48	$8.28	$5.24	$1.90
1994	$9.74	$9.75	$6.83	$4.85	$1.90
1995	$11.69	$11.10	$5.81	$4.46	$1.90
1996	$12.99	$12.19	$5.08	$4.08	$1.90
1997	$14.29	$13.27	$4.94	$3.69	$1.90
1998	$15.91	$14.62	$4.94	$3.49	$1.90
1999	$17.21	$15.98	$4.94	$3.30	$1.90
2000	$18.84	$17.33	$4.94	$3.30	$1.90
2001	$20.23	$18.58	$4.94	$3.30	$1.90
2002	$21.74	$19.95	$4.94	$3.30	$1.90
2003	$23.19	$21.27	$4.94	$3.30	$1.90
2004	$24.70	$22.58	$4.94	$3.30	$1.90
2005	$26.15	$23.90	$4.94	$3.30	$1.90
2006	$27.64	$25.24	$4.94	$3.30	$1.90
2007	$29.11	$26.55	$4.94	$3.30	$1.90
2008	$30.59	$27.88	$4.94	$3.30	$1.90
2009	$32.06	$29.20	$4.94	$3.30	$1.90
2010	$33.54	$30.53	$4.94	$3.30	$1.90
2011	$35.01	$31.85	$4.94	$3.30	$1.90
2012	$36.49	$33.17	$4.94	$3.30	$1.90
2013	$37.96	$34.49	$4.94	$3.30	$1.90
2014	$39.44	$35.82	$4.94	$3.30	$1.90
2015	$40.91	$37.14	$4.94	$3.30	$1.90

- Values for bulk refrigerant (Calm, James E.
Heating/Piping/Air Conditioning, May, 1992) were normalized
to a value of one for 1994. The price of CFC's, HCFC's, and
HFC's from a DuPont distrubutor, Williams and Co., as of
May 5, 1994 were then applied to the resulting table.
- The resulting costs for refrigerants consider only The
trends that were considered in formulation of the estimate
by Calm.

Cost of Commercial Refrigerants

120
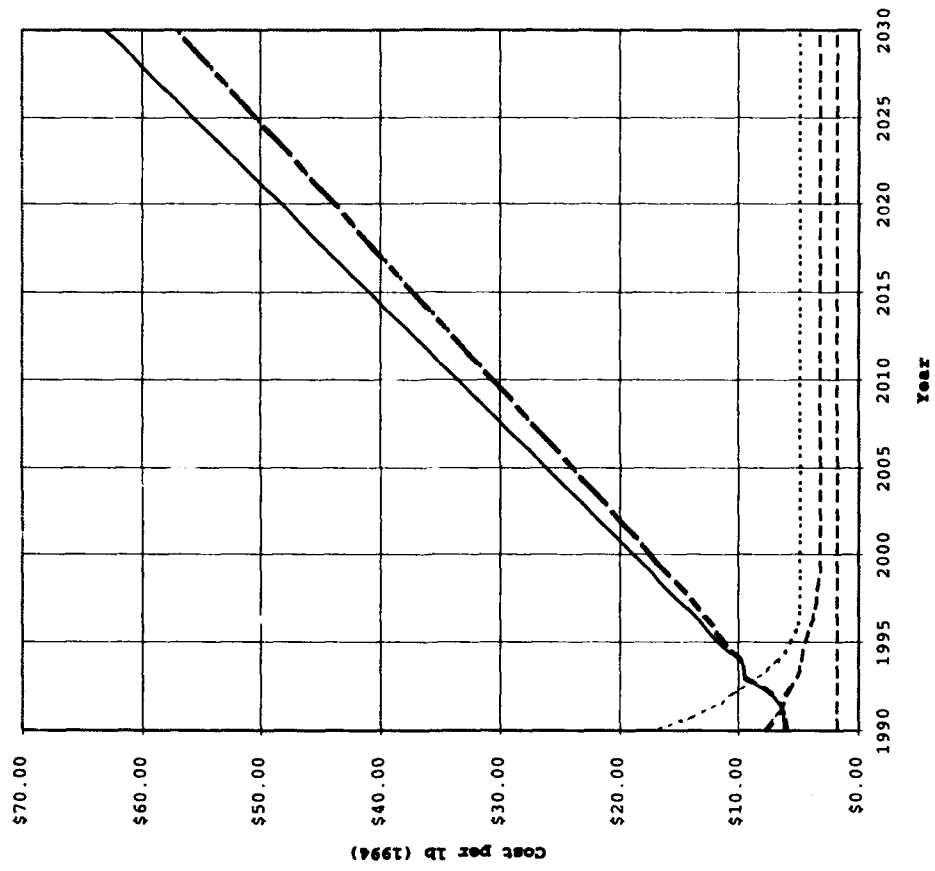
Appendix E - Model Validation Calculations

EXISTING CHILLER

Chiller Capacity	300 tons
Power Requirement	0.83 Kw/ton
Additional Years Chiller Operated	1 years

Run Time	2280 hrs/year
Electricity Cost	$0.02111 per kw-hr
Interest Rate	7%
Refrigerant	CFC-11

Year	Estimated Value	Operation Cost	Maintenance					Salvage Value
			Labor	Periodic Parts	Refrigerant	Labor	Non-Periodic Parts	
0	$2,725	$0	$0	$0	$0	$0	$0	$3,192
1		$11,985	$2,880	$100	$702	$0	$0	
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($277)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$0
Annual Capital Recovery with Return for Refrigerant	$702
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$15,389

122

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time 2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost $0.02111 per kw-hr
Additional Years Chiller Operated	2 years	Interest Rate 7%
		Refrigerant CFC-11

Year	Estimated Value	Operation Cost	Maintenance				Non-Periodic Parts	Salvage Value
			Periodic Labor	Periodic Parts	Refrigerant	Labor		
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	$3,504
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal ($186)

Annual Capital Recovery with Return: Non-Periodic Maintenance $7,443

Annual Capital Recovery with Return for Refrigerant $739

Annual Operating Costs $11,985

Annual Maintenance Cost $2,980

Total Annual Cost $22,961

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time	2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost	$0.02111 per kw-hr
Additional Years Chiller Operated	3 years	Interest Rate	7%
		Refrigerant	CFC-11

Year	Estimated Value	Operation Cost	Maintenance Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	$3,816
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($149)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$5,128
Annual Capital Recovery with Return for Refrigerant	$776
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$20,720

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time	2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost	$0.02111 per kw-hr
Additional Years Chiller Operated	4 years	Interest Rate	7%
		Refrigerant	CFC-11

			Maintenance					
	Estimated	Operation	Periodic	Periodic		Non-Periodic	Non-Periodic	Salvage
Year	Value	Cost	Labor	Parts	Refrigerant	Labor	Parts	Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	$4,206
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($143)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,973
Annual Capital Recovery with Return for Refrigerant	$816
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$19,611

125

EXISTING CHILLER

Chiller Capacity	300 tons
Power Requirement	0.83 Kw/ton
Additional Years Chiller Operated	5 years

Run Time	2280 hrs/year
Electricity Cost	$0.02111 per kw-hr
Interest Rate	7%
Refrigerant	CFC-11

Year	Estimated Value	Operation Cost	Maintenance Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	$4,517
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($121)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,282
Annual Capital Recovery with Return for Refrigerant	$854
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$18,980

EXISTING CHILLER

Chiller Capacity	300 tons	
Power Requirement	0.83 Kw/ton	
Additional Years Chiller Operated	6 years	
Run Time	2280 hrs/year	
Electricity Cost	$0.02111 per kw-hr	
Interest Rate	7%	
Refrigerant	CFC-11	

Year	Estimated Value	Operation Cost	Labor	Periodic Parts	Refrigerant	Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	$4,907
7								
8								
9								
10								
11								
12								
13								
14								
15								

(columns for Labor/Periodic Parts grouped under "Periodic"; Refrigerant, Labor/Non-Periodic Parts grouped under "Maintenance" and "Non-Periodic")

Annual Capital Recovery with Return: Procurement and Disposal	($114)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$2,823
Annual Capital Recovery with Return for Refrigerant	$893
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$18,566

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time: 2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost: $0.02111 per kw-hr
Additional Years Chiller Operated	7 years	Interest Rate: 7%
		Refrigerant: CFC-11

Year	Estimated Value	Operation Cost	Maintenance Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$0	$0	$5,242
8								
9								
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($100)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$2,497
Annual Capital Recovery with Return for Refrigerant	$930
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$18,291

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time	2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost	$0.02111 per kw-hr
Additional Years Chiller Operated	8 years	Interest Rate	7%
		Refrigerant	CFC-11

Maintenance

Year	Estimated Value	Operation Cost	Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	$5,604
9								
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($90)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,964
Annual Capital Recovery with Return for Refrigerant	$966
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$19,805

129

EXISTING CHILLER

			Run Time	2280 hrs/year
Chiller Capacity	300 tons		Electricity Cost	$0.02111 per kw-hr
Power Requirement	0.83 Kw/ton		Interest Rate	7%
Additional Years Chiller Operated	9 years		Refrigerant	CFC-11

Year	Estimated Value	Operation Cost	Periodic Labor	Periodic Parts	Maintenance Refrigerant	Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	
9		$11,985	$2,880	$100	$1,391	$0	$0	$5,952
10								
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal   ($79)
Annual Capital Recovery with Return: Non-Periodic Maintenance $3,633
Annual Capital Recovery with Return for Refrigerant $1,002
Annual Operating Costs $11,985
Annual Maintenance Cost $2,980

                        Total Annual Cost $19,521

130

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time	2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost	$0.02111 per kw-hr
Additional Years Chiller Operated	10 years	Interest Rate	7%
		Refrigerant	CFC-11

Maintenance

Year	Estimated Value	Operation Cost	Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	
9		$11,985	$2,880	$100	$1,391	$0	$0	
10		$11,985	$2,880	$100	$1,482	$0	$0	$6,314
11								
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($69)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,370
Annual Capital Recovery with Return for Refrigerant	$1,036
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$19,302

EXISTING CHILLER

Chiller Capacity	300 tons	
Power Requirement	0.83 Kw/ton	
Additional Years Chiller Operated	11 years	

Run Time	2280 hrs/year	
Electricity Cost	$0.02111	per kw-hr
Interest Rate	7%	
Refrigerant	CFC-11	

Maintenance

Year	Estimated Value	Operation Cost	Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	
9		$11,985	$2,880	$100	$1,391	$0	$0	
10		$11,985	$2,880	$100	$1,482	$0	$0	
11		$11,985	$2,880	$100	$1,569	$0	$0	$6,661
12								
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($59)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,157
Annual Capital Recovery with Return for Refrigerant	$1,070
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$19,133

132

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time	2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost	$0.02111 per kw-hr
	12 years	Interest Rate	7%
Additional Years Chiller Operated		Refrigerant	CFC-11

Maintenance

Year	Estimated Value	Operation Cost	Labor	Periodic Parts	Refrigerant	Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	
9		$11,985	$2,880	$100	$1,391	$0	$0	
10		$11,985	$2,880	$100	$1,482	$0	$0	
11		$11,985	$2,880	$100	$1,569	$0	$0	
12		$11,985	$2,880	$100	$1,658	$0	$0	$7,019
13								
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($49)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$2,980
Annual Capital Recovery with Return for Refrigerant	$1,103
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$18,999

133

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time	2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost	$0.02111 per kw-hr
Additional Years Chiller Operated	13 years	Interest Rate	7%
		Refrigerant	CFC-11

			Maintenance					
	Estimated	Operation	Periodic			Non-Periodic		Salvage
Year	Value	Cost	Labor	Parts	Refrigerant	Labor	Parts	Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	
9		$11,985	$2,880	$100	$1,391	$0	$0	
10		$11,985	$2,880	$100	$1,482	$0	$0	
11		$11,985	$2,880	$100	$1,569	$14,400	$0	
12		$11,985	$2,880	$100	$1,658	$0	$0	
13		$11,985	$2,880	$100	$1,746	$0	$0	$7,372
14								
15								

Annual Capital Recovery with Return: Procurement and Disposal	($40)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,597
Annual Capital Recovery with Return for Refrigerant	$1,135
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$19,657

EXISTING CHILLER

Chiller Capacity	300 tons		Run Time	2280 hrs/year
Power Requirement	0.83 Kw/ton		Electricity Cost	$0.02111 per kw-hr
Additional Years Chiller Operated	14 years		Refrigerant	CFC-11

Year	Estimated Value	Operation Cost	Maintenance Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	
9		$11,985	$2,880	$100	$1,391	$0	$0	
10		$11,985	$2,880	$100	$1,482	$0	$0	
11		$11,985	$2,880	$100	$1,569	$0	$0	
12		$11,985	$2,880	$100	$1,658	$14,400	$0	
13		$11,985	$2,880	$100	$1,746	$0	$0	
14		$11,985	$2,880	$100	$1,835	$0	$0	$7,727
15		$11,985	$2,880	$100				

Annual Capital Recovery with Return: Procurement and Disposal	($31)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,438
Annual Capital Recovery with Return for Refrigerant	$1,166
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$19,537

135

EXISTING CHILLER

Chiller Capacity	300 tons	Run Time 2280 hrs/year
Power Requirement	0.83 Kw/ton	Electricity Cost $0.02111 per kw-hr
Additional Years Chiller Operated	15 years	Interest Rate 7%
		Refrigerant CFC-11

Year	Estimated Value	Operation Cost	Maintenance Periodic Labor	Periodic Parts	Refrigerant	Non-Periodic Labor	Non-Periodic Parts	Salvage Value
0	$2,725	$0	$0	$0	$0	$0	$0	
1		$11,985	$2,880	$100	$702	$14,400	$0	
2		$11,985	$2,880	$100	$779	$0	$0	
3		$11,985	$2,880	$100	$857	$0	$0	
4		$11,985	$2,880	$100	$955	$0	$0	
5		$11,985	$2,880	$100	$1,033	$0	$0	
6		$11,985	$2,880	$100	$1,130	$0	$0	
7		$11,985	$2,880	$100	$1,214	$14,400	$2,000	
8		$11,985	$2,880	$100	$1,304	$0	$0	
9		$11,985	$2,880	$100	$1,391	$0	$0	
10		$11,985	$2,880	$100	$1,482	$0	$0	
11		$11,985	$2,880	$100	$1,569	$0	$0	
12		$11,985	$2,880	$100	$1,658	$14,400	$0	
13		$11,985	$2,880	$100	$1,746	$0	$0	
14		$11,985	$2,880	$100	$1,835	$0	$0	
15		$11,985	$2,880	$100	$1,923	$0	$0	$8,079

Annual Capital Recovery with Return: Procurement and Disposal	($22)
Annual Capital Recovery with Return: Non-Periodic Maintenance	$3,301
Annual Capital Recovery with Return for Refrigerant	$1,196
Annual Operating Costs	$11,985
Annual Maintenance Cost	$2,980
Total Annual Cost	$19,439

REPLACEMENT CHILLER

Chiller Capacity	300 tons		Run Time	2280 hrs/year	
Power Requirement	0.65 Kw/ton		Electricity Cost	$0.02111 per kw-hr	
Life of Chiller	30 years		Interest Rate	7%	
			Refrigerant	HCFC-123	

Year	Estimated Value	Operation Cost	Maintenance					
			Labor	Periodic Parts	Refrigerant	Labor	Non-Periodic Parts	Salvage Value
0	$75,000							
1		$9,386	$2,880	$100	$13	$0	$0	
2		$9,386	$2,880	$100	$12	$0	$0	
3		$9,386	$2,880	$100	$11	$0	$0	
4		$9,386	$2,880	$100	$10	$14,400	$0	
5		$9,386	$2,880	$100	$10	$0	$0	
6		$9,386	$2,880	$100	$10	$0	$0	
7		$9,386	$2,880	$100	$10	$0	$0	
8		$9,386	$2,880	$100	$10	$0	$0	
9		$9,386	$2,880	$100	$10	$14,400	$0	
10		$9,386	$2,880	$100	$10	$0	$0	
11		$9,386	$2,880	$100	$10	$0	$0	
12		$9,386	$2,880	$100	$10	$0	$0	
13		$9,386	$2,880	$100	$10	$0	$0	
14		$9,386	$2,880	$100	$10	$14,400	$0	
15		$9,386	$2,880	$100	$10	$0	$0	
16		$9,386	$2,880	$100	$10	$0	$0	
17		$9,386	$2,880	$100	$10	$0	$0	
18		$9,386	$2,880	$100	$10	$0	$0	
19		$9,386	$2,880	$100	$10	$0	$0	
20		$9,386	$2,880	$100	$10	$14,400	$200	
21		$9,386	$2,880	$100	$10	$0	$0	
22		$9,386	$2,880	$100	$10	$0	$0	

REPLACEMENT CHILLER

		Run Time	2280 hrs/year
Chiller Capacity	300 tons	Electricity Cost	$0.02111 per kw-hr
Power Requirement	0.65 Kw/ton	Interest Rate	7%
Life of Chiller	30 years	Refrigerant	HCFC-123

| | Estimated Operation | Maintenance | | | | | Salvage |
| | | Periodic | | | Non-Periodic | | |
Year	Cost	Labor	Parts	Refrigerant	Labor	Parts	Value
23	$9,386	$2,880	$100	$10	$0	$0	
24	$9,386	$2,880	$100	$10	$0	$0	
25	$9,386	$2,880	$100	$10	$14,400	$0	
26	$9,386	$2,880	$100	$10	$0	$0	
27	$9,386	$2,880	$100	$10	$0	$0	
28	$9,386	$2,880	$100	$10	$0	$0	
29	$9,386	$2,880	$100	$10	$0	$0	
30	$9,386	$2,880	$100	$10	$0	$0	$1,178

Annual Capital Recovery with Return: Procurement and Disposal $6,032
Annual Capital Recovery with Return: Non-Periodic Maintenance $2,484
Annual Capital Recovery with Return for Refrigerant $10
Annual Operating Costs $9,386
Annual Maintenance Cost $2,980

                          Total Annual Cost $20,892

138

Bibliography

Arbuckle, J. Gordon and others. Environmental Law Handbook (Twelfth Edition). Rockville MD: Government Institutes, Inc., 1993.

ASHRAE Standard: Number Designation and Safety Classification of Refrigerants. ANSI/ASHRAE 34-1992. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1992.

ASHRAE Standard: Safety Code for Mechanical Refrigeration. ANSI/ASHRAE 15-1992. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1992.

Baumeister, Theodore ed. Mark's Standard Handbook for Mechanical Engineers (Eighth Edition). New York: McGraw-Hill Book Company, 1978.

Bishop, Ferial S., Environmental Protection Agency. Report on the Progress of Regulations to Protect Stratospheric Ozone: Report to Congress, August 1979. Washington: Government Printing Office, 1979

Blakely, Kimberly. Project Manager, Julian Speer Co., Columbus OH. Telephone interview. 22 Aug 1994.

Burns, Belinda. Tax Manager, Coopers and Lybrand, Dayton OH. Telephone interview. 23 May 1994.

Calm, James E. "Alternative Refrigerants: Challenges, Opportunities," Heating/Piping/Air Conditioning, 64: 38-49 (May 1992).

Calm, James R. Consulting Engineer, Great Falls VA. Telephone interview. 3 June 1994.

CFC Update. Product information CFC-UD-17. La Crosse WI: The Trane Company, Division of American Standard, Inc., Volume 17, April 1994.

Copenhagen Revisions to the Montreal Protocol, November 25, 1992. Environmental Protection Agency, CFC Hotline.

CRWC: Certified Centrifugal or Rotary Screw Water-Chilling Packages. Arlington VA: Air-Conditioning & Refrigeration Institute, 31 May, 1994.

Elkins, Charles. Salesman, C.F.C. Reclamation of Columbus, Columbus OH. Telephone interview. 10 June 1994.

Environmental Protection Agency. "Protection of Stratospheric Ozone; Final Rule," Federal Register, 58: 65017-65078 (December 10, 1993).

Environmental Protection Agency. Protection of Stratospheric Ozone. 40 CFR 82. Washington: GPO, 1993.

Fabrycky, Walter J. and G.J. Thuesen. Economic Decision Analysis. Englewood Cliffs NJ: Prentice-Hall, Inc., 1974.

Fenecy, William. Applications Engineer, Centrifugal Chillers, SnyderGeneral Corp., Minneapolis MN. Telephone interview. 17 May 1994.

Financial Accounting Standards: Original Pronouncements as of July 1, 1977. ARB No.43. Stamford CT: Financial Accounting Standards Board, 1977.

Fitzharris, Kevin. Salesman, Pickrel Brothers, Inc., Dayton OH. Telephone interview. 6 June 1994.

Flaherty, Kenneth. Senior Sales Engineer, Stoffel Equipment Co., Columbus OH. Telephone interview. 7 April 1994.

Flaherty, Kent. Sales Engineer, Stoffel Equipment Co., Columbus OH. Telephone interview. 22 August 1994.

Fredrick, Laurence W. and Robert H. Baker. Astronomy (Tenth Edition). New York: D. Van Nostrand Company., 1976.

"Freon price hike has usually cool customers burning up," The Columbus Dispatch, 10 July 1994, sec. c:7.

Godish, Thad. Air Quality (Second Edition). Chelsea MI: Lewis Publishers, Inc., 1991.

Grant, Eugene L. and others. Principles of Engineering Economy (Sixth Edition). New York: The Ronald Press Company, 1976.

Gushee, David E. CFC Phaseout: Future Problem for Air Conditioning Equipment. Unpublished Report No. 93-3825. Congressional Research Service, Washington, 1 April 1993.

Hanson, Alan. Mechanical Engineer, Newark Air Force Base, Newark OH. Telephone interview. 10 June 1994.

Heider, Sam. Buyer, Dayton Metal Recycling, Inc., Dayton OH. Telephone interview. 7 June 1994.

Hill, Rick. Supervisor of Rates, The Dayton Power and Light Company, Dayton OH. Telephone interview. 18 July 1994.

Holman, Jack Phillip. Thermodynamics (Second Edition). New York: McGraw-Hill Book Company, 1974.

Hsieh, Jui Sheng. Principles of Thermodynamics. Washington: Scripta Book Company, 1975.

Jamison, Michael. Principal Service Engineer, The Trane Co., La Crosse WI. Telephone interview. 17 May 1994.

Keenan, Joseph H. Thermodynamics. New York: John Wiley & Sons, Inc., 1941.

Kieso, Donald E. And Jerry J. Weygandt. Intermediate Accounting (Seventh Edition). New York: John Wiley & Sons, Inc., 1992.

Komarek, Mark. Technical Service Engineer, The Trane Co., La Crosse WI. Telephone interview. 8 June 1994.

McKay, Frank. Team B1, Zone B Supervisor, Wright-Patterson Air Force Base, Dayton OH. Personal interview. 25 May 1994.

Murray, Scott. "Air-Conditioner Firms Put Chill on Plans To Phase Out Use of Chlorofluorocarbons," The Wall Street Journal, 10 May 1993, sec. B:1,2.

Miller, John. Asst. General Manager, I.H. Schlezinger Inc., Columbus OH. Telephone interview. 22 August 1994.

Molina, Mario J. and F.S. Rowland. "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atomic-Atalysed Destruction of Ozone," Nature, 249:810-812 (June 28, 1974).

Nagengast, Bernard. "A Historical Look At CFC Refrigerants," ASHRAE Journal, 30: 37-39 (November 1988)

Needles, Belverd E. Financial Accounting (Fourth Edition). Boston: Houghton Mifflin Co., 1992.

Ozone Secretariat. Handbook for the Montreal Protocol on Substances That Deplete the Ozone Layer (Third Edition). Nairobi Kenya: United Nations Environmental Programme, 1993.

Rapier, Mark H. Sales Manager, Dayton Sales District, The Trane Co., Dayton OH. Personal interview. 14 April, 1994.

Revisited: The Search for Chiller Efficiency. Engineers Newsletter, Vol. 23, No. 1. La Crosse WI: Commercial Systems Group, The Trane Co., 1994.

Salas, Carl E. and Maruanne Salas. Guide to Refrigeration CFC's. Lilburn GA: The Fairmont Press, Inc., 1992.

Salvendy, Gavriel ed. Handbook of Industrial Engineering. New York: John Wiley & Sons, Inc., 1982.

Scheskie, Art. Communications Manager, Commercial Systems Group, The Trane Co., La Crosse WI. Telephone interview. 9 June 1994.

Schmidtt, Andrew. Customer Service Representative, General Electric Co., Schenectady NY. Telephone interview. 4 May 1994.

Seinfeld, John H. Atmospheric Chemistry and Physics of Air Pollution. New York: John Wiley & Sons, Inc., 1986.

Spiller, Earl A. Financial Accounting: Basic Concepts (Third Edition). Homewood IL: Richard D. Irwin, Inc., 1977.

Stoecker, Wilbert F. and Jerold W. Jones. Refrigeration and Air Conditioning. New York: McGraw-Hill Book Company, 1982.

Threlkeld, James L. Thermal Environmental Engineering (Second Edition). Englewood Cliffs NJ: Prentice-Hall Inc., 1970.

Tuchnowski, Tom. Senior Sales Engineer, York International Corp., Cincinnati OH. Telephone interview. 19 April 1994.

United States Congress. Tax Reform Act of 1986. Public Law 99-514, 99th Congress, 2nd Session, 1986. Washington: GPO, 1986.

United States Congress. Omnibus Budget Reconciliation Act of 1990. Public Law 101-508, 101st Congress, 2nd Session, 1990. Washington: GPO, 1990.

United States Congress. Clean Air Act Amendments of 1990. Public Law 101-549, 101st Congress, 2nd Session, 1990. Washington: GPO, 1990.

United States Congress. Energy Policy Act of 1992. Public Law 102-486, 102nd Congress, 2nd Session, 1992. Washington: GPO, 1992.

United States House of Representatives. <u>Conference Report on PL 95-95, The Clean Air Act Ammendments.</u> House Report No. 95-564 to HR-6161, 95th Congress, 1st Session, 1977. Washington: GPO, 1977.

United States Senate. <u>Montreal Protocol on Substances that Deplete the Ozone Layer.</u> Senate Treaty Document 100-10, 100th Congress, 1st Session, 1987. Washington: GPO, 1987.

United States Senate. <u>Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (London Amendments).</u> Senate Treaty Document 102-4, 102nd Congress, 1st Session, 1991. Washington: GPO, 1991.

Van Wylen, Gordon J. and Richard E. Sonntag. <u>Fundamentals of Classical Thermodynamics</u> (Second Edition). New York: John Wiley & Sons, Inc., 1973.

Wenzlick, Leeann. Rates Analyst, The Dayton Power and Light Company, Dayton OH. Personal correspondence. 19 July 1994.

Wilson, Duncan. Sales Representative, Williams and Company, Columbus OH. Personal interview. 5 May 1994.

Wood, Bernard W. <u>Applications of Thermodynamics.</u> Reading MA: Addison-Wesley Publishing Co., 1969.

York International. <u>Solid Environmental Solutions For Today's Refrigerant Challenges.</u> HVAC&R Engineering Update Form 160.46-PM6 (193). York PA: York International Corp., 1993.

Zadow, Marty. President, Chiller Source Marketing, The Trane Co., Charlotte NC. Telephone interview. 10 June 1994.

Zelinski, Jeff. Mechanical Engineer, Wright-Patterson AFB OH. Telephone interview. 31 May 1994.

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	15 Sep 94	Final Report

4. TITLE AND SUBTITLE

Economics of Chlorofluorocarbon (CFC) Machine Replacement

5. FUNDING NUMBERS

6. AUTHOR(S)

Geoffrey D. Rudderow

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

AFIT/ENV
2950 P Street
Wright-Patterson AFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GEE/ENV/94S-22

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Continued use of chlorofluorocarbon (CFC) refrigerants may have a severe financial as well as operational impact on the users of air-conditioning and other refrigeration equipment as price increases continue and production is phased out. With production of CFC's coming to a halt on 31 December 1995, the two major refrigerants that have been used in commercial and industrial cooling applications will no longer be available. The phase out of production is a result of national and international agreement that these, as well as other CFC's, are a primary cause of the depletion of the stratospheric ozone layer. To help the user reduce this impact, an economic model based on the time value of money and utilizing replacement analysis was developed. The model is designed to require the user to supply information on his own equipment and on the projected costs of non-CFC replacement equipment. After running the model, the point in time when the existing equipment should be replaced is indicated. By way of example, the model is applied to a centrifugal chiller application. The results of this approach indicate that the increase in CFC costs is only a small factor in the cost of chiller operation. Rather than make a replacement to avoid the high price of refrigerant, the controlling factor is the overall cost of power consumption required to provide the cooling effect.

14. SUBJECT TERMS

chlorofluorocarbons, CFC's, ozone depleting chemicals, ODC's, refrigeration, air conditioning, HVAC

15. NUMBER OF PAGES

150

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL